<html><head><title>Object moved</title></head><body>
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XIII

This agreement is binding on the successors and assigns of the respective parties hereto.

XIV

If any part of this agreement is for any reason held to be illegal, invalid, or unenforceable, such illegality, invalidity, or unenforceability shall not affect any other provision, but this agreement shall be construed and enforced as if such illegal, invalid, or unenforceable provisions had not been contained herein. Any constitutional or statutory provision enacted after the date of this agreement which validates or makes legal any provision herein shall be deemed to apply hereto.

XV

The Municipalities shall not grant a franchise for the collection of solid waste within their boundaries, which would circumvent the intent of this agreement for the disposal of solid waste by the Parish, it being the intent hereof that the exclusive disposal of the Municipalities' solid waste by the Parish, whether or not collected by the Municipalities, is the inducement for the acquisition and construction of the facilities by the Parish at its sole expense.

IN WITNESS WHEREOF, the parties hereto have caused these presents to be executed by their respective officers thereunto duly authorized as of the day and year first above written.

WITNESSES

POLICE JURY OF ST. MARY PARISH
STATE OF LOUISIANA

By ______________________
President

TOWN OF BALDWIN, LOUISIANA

By ______________________
Mayor

TOWN OF BERWICK, LOUISIANA

By ______________________
Mayor

CITY OF FRANKLIN, LOUISIANA

By ______________________
Mayor

CITY OF MORGAN CITY, LOUISIANA

By ______________________
Mayor

TOWN OF PATTERSON, LOUISIANA

By ______________________
Mayor

XIII

This agreement is binding on the successors and assigns of the parties hereto.

XIV

If any part of this agreement is for any reason held to ill valid, or unenforceable, such illegality, invalidity, or unenforceabilit not affect any other provision, but this agreement shall be construed an as if such illegal, invalid, or unenforceable provisions had not been co herein. Any constitutional or statutory provision enacted after the dat agreement which validates or makes legal any provision herein shall be c apply hereto.

XV

The Municipalities shall not grant a franchise for the collect solid waste within their boundaries, which would circumvent the intent c agreement for the disposal of solid waste by the Parish, it being the in that the exclusive disposal of the Municipalities' solid waste by the Pa ther or not collected by the Municipalities, is the inducement for the a and construction of the facilities by the Parish at its sole expense.

IN WITNESS WHEREOF, the parties hereto have caused these prese be executed by their respective officers thereunto duly authorized as of and year first above written.

WITNESSES

POLICE JURY OF ST. MARY PARIS
STATE OF LOUISIANA

Bettye Doucard

By ______________
President

TOWN OF BALDWIN, LOUISIA

By ______________
Mayor

TOWN OF BERWICK, LOUISIANA

By ______________
Mayor

CITY OF FRANKLIN, LOUISIANA

Yvonne Martin

By ______________
Mayor

CITY OF MORGAN CITY, LOUISIANA

By ______________
Mayor

TOWN OF PATTERSON, LOUISIANA

By ______________
Mayor

IX

The Parish shall keep accurate records of all solid waste delivered to the solid waste disposal facilities and the tonnage contributed by each user (including the Parish) and shall perform all necessary record keeping, billing and other accounting duties. Municipalities shall have the right to inspect, upon the giving of reasonable notice, any and all records (financial or otherwise) of the Parish relating to the operation and maintenance of the facilities. In accounting for the cost of operating the solid waste disposal facilities, all relevant costs, direct and indirect, shall be taken into account including, but not by way of limitation, a proper amount for depreciation of those components of the facilities which are expected to require replacement administrative costs and insurance.

X

The solid waste disposal facilities shall be operated, maintained and managed on behalf of the Parish by its Director of Public Works in compliance with all applicable Federal and State laws and regulations. The facilities shall be maintained in good working order by the Parish at all times, including provisions for access to and from the facilities. The Parish may contract with industries and private parties for the use of the solid waste disposal facilities at such fees and charges, and under such terms as determined by the Parish. Fees and charges established for industrial and other users shall fairly reflect such non-governmental user's share of the total costs of the facilities proportionate to its intended use. No contract with any non-governmental user shall ever impair the availability and access to the facilities by Municipalities or any other political subdivision contracting with the Parish for the use of the facilities.

XI

The Parish and the Municipalities shall provide, establish, operate, maintain, regulate and finance their separate and individual solid waste collection services, except as otherwise set forth herein.

The Municipalities' collection services shall serve only the areas within their respective municipal political jurisdiction. The solid waste collection services provided by the Parish shall serve the unincorporated areas of the Parish.

The parties hereto reserve the right to contract, individually or collectively, with any other party, including other political subdivisions and municipalities, for the performance of solid waste collection services, subject to the restriction contained in Article V herein. All vehicles employed for transporting solid waste, whether used for solid waste collection services or as part of the solid waste disposal facilities shall comply with any and all applicable state and local health laws, regulations, and ordinances. All such vehicles shall be capable of self-ejecting or dumping their load into a stationary hopper or other receptacle and must be physically compatible with the receiving containers and equipment of the Parish located at the sites of the various components of the solid waste disposal system. The parties hereto shall coordinate their solid waste collection services so as to permit timely and proper loadings for the proposed transport vehicle operations and/or milling plant and landfill operations.

XII

This agreement shall not be abrogated or modified nor shall any of the rights and obligations hereunder be transferred or assigned without the written consent of all parties hereto.

This agreement is binding on the successors and assigns of the re parties hereto.

XIV

If any part of this agreement is for any reason held to be [illegible]ga. valid, or unenforceable, such illegality, invalidity, or unenforceabi[illegible] s[illegible] not affect any other provision, but this agreement shall be construed and e[illegible] as if such illegal, invalid, or unenforceable provisions had not been conta[illegible] herein. Any constitutional or statutory provision enacted after the date o[illegible] agreement which validates or makes legal any provision herein shall be deem[illegible] apply hereto.

XV

The Municipalities shall not grant a franchise for the collection solid waste within their boundaries, which would circumvent the intent of t[illegible] agreement for the disposal of solid waste by the Parish, it being the inten[illegible] that the exclusive disposal of the Municipalities' solid waste by the Paris[illegible] ther or not collected by the Municipalities, is the inducement for the acqu[illegible] and construction of the facilities by the Parish at its sole expense.

IN WITNESS WHEREOF, the parties hereto have caused these presents be executed by their respective officers thereunto duly authorized as of the and year first above written.

WITNESSES

POLICE JURY OF ST. MARY PARISH
STATE OF LOUISIANA

By ______________________
President

TOWN OF BALDWIN, LOUISIANA

By ______________________
Mayor

TOWN OF BERWICK, LOUISIANA

By ______________________
Mayor

CITY OF FRANKLIN, LOUISIANA

By ______________________
Mayor

CITY OF MORGAN CITY, LOUISIANA

By ______________________
Mayor

TOWN OF PATTERSON, LOUISIANA

By ______________________
Mayor

2. "NONPUTRESCIBLE WASTE" means all solid waste other than putrescible waste.

3. "PUTRESCIBLE WASTE" means waste materials containing organic matter that is subject to rapid decomposition by fungi and bacteria, such as food waste and dead animals.

4. "SOLID WASTE COLLECTION SERVICES" - The periodic removal and collection of solid waste materials, which are usually assembled in containers at individual residences, institutions, commercial establishments and industrial plants, by placement in vehicles which are designed for this purpose and then transported to a receiving facility in the disposal system. This definition does not include the intermittent delivery of small quantities of solid waste materials to certain designated receiving facilities by private persons from their own residences. COLLECTION SERVICES as defined are not part of the solid waste disposal facilities of the Parish as hereafter defined.

5. "SOLID WASTE" means all of the waste materials from the community, except liquid waste (sewage); for the purpose of this Agreement - solid waste shall be differentiated and classified as follows, to-wit:

(a) "GARBAGE" - all usual household, institutional and light commercial waste products, normally a mixture of both putrescible and nonputrescible materials, EXCEPT bulky, nonputrescible waste products such as discarded furniture, appliances, large crates and packing boxes, etc.

(b) "RUBBISH" (trash) - nonputrescible household, institutional, and light commercial waste products containing a high percentage of combustible materials such as small vegetation, paper products and small packaging materials.

(c) "BULKY WASTES" - nonputrescible household, institutional, and light commercial waste products such as discarded furniture, appliances, vehicle tires and parts, bicycles, metal cable, large crates and packing boxes, trees, stumps, etc.

(d) "INDUSTRIAL WASTE" - all solid waste products of industry, from both on-shore and off-shore operations, and including demolition, construction, fabrication, process, street and alley, and miscellaneous waste, EXCEPT special waste as defined herein.

(e) "SPECIAL WASTE" - hazardous or toxic by-products and discarded waste materials from industrial operations, whether in a solid, liquid, semi-liquid or gaseous state, such as radioactive materials, explosives, certain metals, tar, paints, solvents, sludge, fumes, etc.; pathological waste from the operation of medical clinics, hospitals, abattoirs, dog pounds, and similar sources, such as human and animal remains, contaminated clothing, instruments, floor sweepings, food waste, etc.; putrescible organic waste from food processing plants such as slaughter houses, vegetable, animal and marine life canneries and similar processes; abandoned or discarded vehicles of all kinds.

(f) "FARM WASTE" - all organic waste products generated from agricultural and ranching production operations that are stored or disposed of at such locations and in such a manner as not to create a public nuisance or endanger the public health.

V

Each Municipality and the Parish agrees that it will use only the solid waste disposal facilities and said facilities shall be the sole and exclusive means employed by each Municipality and the Parish for disposal of its solid wastes, unless otherwise agreed upon in writing by Parish and Municipa

VI

The Parish and Municipalities will be charged for the disposal of solid waste on the basis of the tonnage delivered to the facilities and acce by the Parish for disposal. All revenues from such charges shall be used sc for the operation, administration and maintenance of the facilities includi serves for depreciation and replacement of equipment, improvements, works ar facilities and machinery of the solid waste disposal facilities. Depreciati shall be determined in accordance with standard life tables of depreciation. Parish shall not include in the cost per ton any payments to amortize any de curred or to reimburse any capital expended for the construction and acquis of the solid waste disposal facilities. The parties hereto agree to pay the following amounts for the disposal of their solid waste under the terms of Agreement:

(a) During the first twelve months of operation of the facilities the cost per ton of solid waste delivered to and accepted by the Parish for disposal will be $11.70; provided, however, that if the Parish determines after the first six months of operation that the cost per ton will be insufficient to fully pay the cost of operati and maintaining the facilities, the Parish may increase the cost per ton for the remaining six months subject to approval by the Municipalities.

(b) After the first twelve months of operation, the cost pe n shall be calculated for each year thereafter as follows:

The total costs for the preceeding year of operation after deducting any revenues from industrial and individual users of the facilities, shall be divided by the total tonnage delivered by the Parish and the Municipalities during such year and such cost per ton shall be the charge per ton to the parties to this Agreement for the following year. The determination of said cost per ton shall be calculated within 30 days after the end of each twelve month period of operation.

VII

The Parish, as the owner and operator of the solid waste disposal f ties, shall have the right to refuse any solid wastes it deems not acceptable processing by the facilities. All waste materials entering the solid waste processing by the facilities shall be weighed at the scale station provided for that purp plant or landfill shall be weighed at the scale station provided for that purp at the point of entry, and records of the weight, date, identity of the user (Parish, Municipality, Industry), and other pertinent data shall be kept. All waste will be delivered to the Parish solid waste disposal facilities in accor with the procedures, schedules and regulations designated and prescribed by th Director of the Department of Public Works of St. Mary Parish and pursuant to provisions of the Solid Waste Management Ordinance of St. Mary Parish, Louisia Any Municipality or other user availing itself of the said facilities shall de its solid waste to the points designated by the Parish in accordance with such ordinances and regulations. The Parish, through its Director of Public Works, publish in convenient form such ordinances and regulations and distribute them the Municipalities and any other interested person. Such regulations, unless wise provided therein, shall have binding effect immediately upon issuance.

VIII

Each Municipality shall be billed on a monthly basis for the respec quantity (tons) of solid waste delivered and such charges shall be due and p

STATE OF LOUISIANA

PARISH OF ST. MARY

SOLID WASTE DISPOSAL AGREEMENT

This Agreement made and entered into, in 5 multiple originals, as of this 28 day of July, 1976, by and between:

THE PARISH OF ST. MARY, STATE OF LOUISIANA, a political subdivision of the State hereinafter called the "Parish", acting by and through the President of the Police Jury of said Parish, the governing authority thereof, pursuant to the provisions of a resolution adopted by the Police Jury on July 28, 1976.

and

THE CITIES OF FRANKLIN AND MORGAN CITY, LOUISIANA AND THE TOWNS OF BALDWIN, BERWICK AND PATTERSON, LOUISIANA, political corporations and subdivisions of the State of Louisiana, hereinafter called "Municipalities", acting by and through their duly empowered and authorized Mayors pursuant to the provisions of resolutions adopted by the governing authorities of said Municipalities.

WHEREAS, the Parish has begun the financing, acquisition and construction of solid waste disposal facilities in the Parish, consisting of transfer station, transfer conveyances, milling plant, wastewater treatment facility(s), landfill, sites and related equipment and machinery therefor (hereinafter referred to as the "solid waste disposal facilities"); and

WHEREAS, said solid waste disposal facilities will be used for the benefit of the incorporated and unincorporated areas of the Parish; and

WHEREAS, the Municipalities require adequate facilities to dispose of the solid waste collected by them to comply with applicable federal guidelines and State Department of Health Regulations; and

WHEREAS, pursuant to Part VII, Chapter 2, Title 33 of the Louisiana Revised Statutes of 1970, Parish and Municipalities may make arrangements in order to create greater efficiency and economy in, and to further the extension of services in the area of solid waste disposal; and

WHEREAS, by entering into this Agreement, the Municipalities will avoid the necessity of constructing and acquiring their own individual disposal facilities and thereby afford greater savings to their citizens and reduce their per capita costs for solid waste disposal; and

WHEREAS, Municipalities wish to induce and encourage the Parish to complete the acquisition, construction and financing of the solid waste disposal facilities and assure the Parish that Municipalities will use said facilities upon their completion;

NOW, THEREFORE, for and in consideration of the mutual covenants herein contained, the parties hereto agree as follows:

I

For the purpose of this Agreement, the words and terms as herein used shall have the following meanings:

I. "HEREIN", "HERETO", AND "HEREOF" refer to the entire agreement, unless the context clearly indicates otherwise.

5. "SOLID WASTE DISPOSAL FACILITIES" or "FACILITIES" means, unless the context clearly otherwise indicates, the facilities of the Parish composed of the following components, including all vehicles, compactors, equipment, containers machinery, appurtenances and sites necessary therefor:

(a) "TRANSFER STATIONS" - the site or sites to be designated by the Parish at which waste materials are transferred from collection vehicles into large capacity vehicles for transport to the milling plant or landfill.

(b) "TRANSPORT VEHICLES" - large capacity vehicles owned by the Parish and used to transport solid waste from the Transfer Stations or other parts of the Parish to the Milling Plant and/or Landfill. Small capacity vehicles used for Collection Services by the Police Jury of the Parish in serving unincorporated areas are not part of the solid waste disposal facilities as herein defined.

(c) "LANDFILL" - one or more sites at which milled or shredded waste materials and/or non-shredded waste materials are placed, compacted and graded to a predetermined height or depth and on which a final cover of earth is placed.

(d) "MILLING PLANT" - the facility in which garbage and rubbish will be processed by shredding or grinding into small pieces. A volume reduction mechanical process for garbage and rubbish.

(e) "WASTEWATER TREATMENT FACILITY(S)" - a plant, oxidation pond or other approved facility in which seepage water (leachate), runoff water from the landfill, and wastewater from the milling plant is processed, treated or purified in such a manner that it will become inoffensive and noninjurious to plant and animal life.

II

The Parish agrees to plan, acquire, construct, finance, operate and maintain the solid waste disposal facilities. The entire cost of the acquisition and construction of the facilities will be paid by the Parish from its share of the avails or proceeds of the 3/4% sales and use tax being levied and collected by the Parish pursuant to the authority of a special election held c December 11, 1973, and other revenues as necessary. The costs of maintaining and operating said facilities as more fully hereinafter defined will be paid solely from fees and charges levied upon and collected from users of the facil ties (including the Parish and Municipalities) which fees and charges shall be determined according to the provisions of this contract.

III

This Agreement shall be valid and binding upon the parties hereto the date first written above, until January 1, 1999, provided, however, that til the solid waste disposal facilities have been completed and are ready fo operation, and notification thereof given to the Municipalities by the Paris no solid waste will be delivered to the solid waste disposal facilities by t Municipalities or accepted by the Parish for disposal.

IV

The Parish, in consideration of the sums to be paid by Municipali hereinafter set forth in Article VI of this Agreement, hereby agrees to rece process and dispose of the solid waste collected by the Municipalities and d livered to the Parish solid waste disposal facilities in accordance with the and provisions of this Agreement. Special waste and farm waste as defined i ticle I shall not be accepted by the Parish for disposal.

ORDINANCE NO. 1101

An Ordinance prohibiting persons from removing, picking up or transferring recyclable materials left at curbside in containers, and providing penalties for violation of same.

BE IT ORDAINED by the St. Mary Parish Council in regular session convened:

SECTION 1. No person or persons, other than the current resident of the property on which the items are placed, or an authorized carrier, shall remove, pick up, or transfer recyclable materials left at curbside in any residential subdivision, or at curbside at any single-family residence. Materials left at curbside, in either specifically marked recovery containers or other type of container, are to be picked up by a designated carrier for the purpose of removal of recyclable materials. Materials referred to, and to be left at curbside in specifically marked containers will include, but not be limited to, glass, newspaper and aluminum.

SECTION 2. Each removal of an item or items from residential subdivision residence location or a single-family residence located shall constitute a separate violation of this section. Unauthorized persons removing materials or bins other than those persons designated above shall be fined as follows:

(1) Upon first conviction of violation of this section, the person shall be fined twenty-five ($25.00) dollars for each such violation.

(2) Upon second conviction of violation of this section, the person shall be fined fifty ($50.00) dollars for each such violation.

(3) Upon third and subsequent convictions of violation of this section, the person shall be fined one hundred ($100.00) dollars for each such violation.

SECTION 3. All ordinance or parts of ordinances in conflict herewith are hereby repealed.

This ordinance having been offered and read on this the 9th day of May, 1990; having been published in accordance with law; and having been heard in a public hearing held at Franklin, Louisiana on the 13th day of June, 1990; was adopted by the following vote on the 13th day of June, 1990.

AYES: Joseph Davis, Chuck Rogers, Emory Jennings, James Russo, Henry Steckler, Loylis Duhon, H. V. Fondren, Robert McHugh and Harold Clausen.

NAYS: None.

ABSENT: Gary Wiltz and Mike Taylor.

APPROVED:

HAROLD G. CLAUSEN, CHAIRMAN
ST. MARY PARISH COUNCIL

ATTEST:

KIMBERLY W. PUSATERI, CLERK
ST. MARY PARISH COUNCIL

This Ordinance was submitted to the President of St. Mary Parish on this the 15th day of June, 1990 at the hour of 2:21pm

APPROVED:

PRESCOTT FOSTER, PRESIDENT
ST. MARY PARISH

This Ordinance was returned to the Clerk of the Council on this the 15th day of June, 1990 at the hour of 3:16pm

ORDINANCE NO. 1103

An Ordinance providing for the disposal of rope, wire rope, and hoses, and providing for penalties for violation of same.

BE IT ORDAINED, in regular session by the St. Mary Parish Council:

SECTION 1: The St. Mary Parish Harold J. "Babe" Landry Reduction and Resource Recovery Facility and the Transfer Station shall accept no rope, wire rope, or hoses of any nature unless same are cut into lengths not exceeding five (5) feet.

SECTION 2. No person, firm, partnership or corporation shall bring onto the premises of the St. Mary Parish Harold J. "Babe" Landry Reduction and Resource Recovery Facility and the Transfer Station nor shall such person, firm, partnership or corporation dump or deposit any rope, wire rope or hoses of any nature unless the same is first cut into lengths not exceeding five (5) feet.

SECTION 3. Any person, firm, partnership or corporation violating the provisions of this Ordinance shall be fined not more than $500 or be imprisoned for not more than six (6) months or both.

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SECTION 4. Nothing provided herein shall eliminate or lessen the obligation of any person, firm, partnership or corporation for damages to persons or property resulting from any disregard of this ordinance.

SECTION 5. All ordinances or parts of ordinances in conflict herewith are hereby repealed.

This ordinance shall become effective upon publication in the Official Journal.

This ordinance having been offered and read on this the 9th day of May, 1990; having been published in accordance with law; and having been heard in a public hearing held at Franklin, Louisiana on the 13th day of June, 1990; was adopted by the following vote on the 13th day of June, 1990.

AYES: Joseph Davis, Chuck Rogers, Emory Jennings, James Russo, Henry Steckler, Loylis Duhon, H. V. Fondren, Robert McHugh and Harold Clausen.

NAYS: None.

ABSENT: Gary Wiltz and Mike Taylor.

APPROVED:

HAROLD G. CLAUSEN, CHAIRMAN
ST. MARY PARISH COUCNIL

ATTEST:

KIMBERLY W. PUSATERI, CLERK
ST. MARY PARISH COUNCIL

This Ordinance was submitted to the President of St. Mary Parish on this the 15th day of June, 1990 at the hour of 2:21pm

APPROVED:

PRESCOTT FOSTER, PRESIDENT
ST. MARY PARISH

This Ordinance was returned to the Clerk of the Council on this the 15th day of June, 1990 at the hour of 3:16pm

ORDINANCE NO. 1132

An Ordinance prohibiting the disposal of whole tires at the Harold J. "Babe" Landry Solid Waste Facility and/or the West End Transfer Station; requiring that same be shredded or cut in half before disposal; and providing penalties for violation of same.

BE IT ORDAINED, by the St. Mary Parish Council, State of Louisiana, acting as the governing authority of said Parish:

SECTION 1. No person, firm, corporation, partnerships or other entity shall dispose of any automobile, truck, farm implement or other tires at the Harold J. "Babe" Landry Solid Waste Facility or the West End Transfer Station without having first had same cut in half or shredded in accordance with rules and regulations promulgated by the Louisiana Department of Environmental Quality.

SECTION 2. Any person desiring to dispose of whole tires may choose to have the same cut or shredded by the said solid waste, in such event the solid waste facility shall charge and the said entity desiring to dispose of same shall be charged and pay fees as follows:

Tipping fees for waste tires be set at $1.00 per tire up to a 16 inch tire, $2.00 per tire up to a 24 inch tire, and $15.00 per tire for any oversize tires.

SECTION 3. Any person who shall violate the provisions hereof.

This ordinance having been offered and read on this 26th day of December, having been published in accordance with law; and having been heard in a public hearing held at Franklin, Louisiana on the 13th day of February, 1991; was adopted by the following vote on the 13th day of February, 1991.

AYES: Gary Wiltz, Chuck Rogers, Ruth Davis, Emory Jennings, Kathy Taylor, James Russo, Henry Steckler, Loylis Duhon, H. V. Fondren, and Harold Clausen.

NAYS: Robert McHugh.

ABSENT: None.

APPROVED:

HAROLD G. CLAUSEN, SR., CHAIRMAN
ST. MARY PARISH COUNCIL

ATTEST:

Kimberly W. Pusateri

KIMBERLY W. PUSATERI, CLERK
ST. MARY PARISH COUNCIL

This Ordinance was submitted to the President of St. Mary Parish on this the 15th day of February, 1991 at the hour of 1:50pm.

APPROVED:

Prescott Foster

PRESCOTT FOSTER, PRESIDENT
ST. MARY PARISH

This Ordinance was returned to the Clerk of the Council on this the 20th day of February, 1991 at the hour of 2:30pm.

ORDINANCE NO. 1148

An ordinance amending Ordinance No. 1108 providing for the disposal of surplus white goods disposed of at the St. Mary Parish Solid Waste Reduction Plant and the Pickup Station.

SECTION 1. The Chief Administration Officer of the Parish of St. Mary is hereby authorized to dispose of "White Goods" from time to time in his/her discretion, by bid, auction, or sale in accordance with law.

SECTION 2. Except as amended herein, the provisions of Ordinance No. 1108 shall remain in full force and effect.

SECTION 3. All ordinances in conflict herewith are hereby repealed.

This ordinance shall become effective upon publication.

This Ordinance having been offered and read on this the 14th day of August, 1991; having been published in accordance with law; and having been heard in a public hearing held at Franklin, Louisiana on the 25th day of September, 1991; was adopted by the following vote on the 25th day of September, 1991:

YEAS: Gary Wiltz, Chuck Rogers, Ruth Davis, Emory Jennings, Kathy Taylor, James Russo, Henry Steckler, Loylis Duhon, H. V. Fondren, Robert McHugh and Harold Clausen.

NAYS: None.

ABSENT: None.

APPROVED:

HAROLD G. CLAUSEN, SR., CHAIRMAN
ST. MARY PARISH COUNCIL

ATTEST:

KIMBERLY W. PUSATERI, CLERK
ST. MARY PARISH COUNCIL

This ordinance was submitted to the President of St. Mary Parish on this the 27th day of September, 1991, at the hour of 1:50 p.m.

APPROVED:

PRESCOTT FOSTER, PRESIDENT
ST. MARY PARISH

This ordinance was returned to the Clerk of the Council on this the 8th day of October, 1991 at the hour of 1:20 p.m.

ORDINANCE NO. 1157

An ordinance amending Ordinance No. 1148 providing for the disposal of all recyclable goods disposed of at the St. Mary Parish Solid Waste Reduction Plant and the Pickup Station.

SECTION 1. The Chief Administrative Officer of the Parish of St. Mary is hereby authorized to dispose of all recyclable goods from time to time in his/her discretion, by bid, auction or sale in accordance with law.

SECTION 2. All ordinances in conflict herewith are hereby repealed.

This ordinance shall become effective upon publication.

This Ordinance having been offered and read on this the 13th day of November, 1991; having been published in accordance with law, and having been heard in a public hearing held at Franklin, Louisiana on the 18th day of December, 1991; was adopted by the following vote on the 18th day of December, 1991.

YEAS: Gary Wiltz, Chuck Rogers, Ruth Davis, Emory Jennings, Patrick Hebert, Henry Steckler, Loylis Duhon, H. V. Fondren, Robert McHugh and Harold Clausen.

NAYS: None.

ABSENT: James Russo.

APPROVED:

HAROLD G. CLAUSEN, SR., CHAIRMAN
ST. MARY PARISH COUNCIL

ATTEST:

KIMBERLY W. PUSATERI, CLERK
ST. MARY PARISH COUNCIL

This ordinance was submitted to the President of St. Mary Parish on this the 20th day of December, 1991 at the hour of 2:50pm.

APPROVED:

PRESCOTT FOSTER, PRESIDENT
ST. MARY PARISH

This ordinance was returned to the Clerk of the Council on this the 2nd day of January, 1992 at the hour of 4:21p.m.

2603

ORDINANCE NO. 1212

An Ordinance providing for the enforcement of collection of garbage collection fees by contract with waterworks districts and/or the filing of property liens, all in accordance with the provisions of Louisiana Law.

BE IT ORDAINED that the Parish of St. Mary, State of Louisiana contract with Waterworks Districts for the collection of garbage collection fees, with the stipulation that water service may be terminated for nonpayment; alternatively or in addition thereto, that liens be filed against those properties failing to pay such garbage collection fees, all in accordance with Louisiana Law.

BE IT FURTHER ORDAINED that the Administration of St. Mary Parish is authorized to negotiate and execute such contracts with Waterworks Districts and to file liens as may be authorized by law.

This ordinance having been offered and read on this the 24th day of February, 1993; having been published in accordance with law; and having been hearing in a public hearing held at Franklin, Louisiana, on the 14th day of April, 1993; was adopted by the following vote on the 14th day of April, 1993.

AYES: H. A. Louviere, Robert Ayres, William Cefalu, Dr. Tim Tregle, Steve Bierhorst and Henry Steckler.

NAYS: Lionel Metz, Scott Ramsey and Albert Foulcard.

ABSENT: Paul Naquin and Larry Besse.

APPROVED:

Albert Foulcard

ALBERT FOULCARD, CHAIRMAN
ST. MARY PARISH COUNCIL

ATTEST:

Kimberly M. Pusateri

KIMBERLY M. PUSATERI, CLERK
ST. MARY PARISH COUNCIL

This Ordinance was submitted to the President of St. Mary Parish on this the 19th day of April, 1993 at the hour of 3:47 p.m.

APPROVED:

Oray P. Rogers

ORAY P. ROGERS, PRESIDENT
ST. MARY PARISH

This Ordinance was returned to the Clerk of the Council on this the 19th day of April, 1993 at the hour of 4:22 p.m.

ORDINANCE NO. 1216

An Ordinance amending and reenacting Ordinance No. 1132 of the Parish of St. Mary, State of Louisiana to prohibit the disposal of whole tires at the Harold J. "Babe" Landry Solid Waste Facility and/or the West End Transfer Station; requiring that same be shredded or cut in half before disposal; and provide penalties for violation of same.

SECTION 1.

Section 2 of Ordinance No. 1132 of St. Mary Parish is hereby amended to read as follows:

Any person, firm, corporation or other entity desiring to dispose of tires or parts of tires at any solid waste facility owned or operated by the Parish of St. Mary, shall be subject to the following charges, to be paid prior to such disposal:

a. If the tires are cut or shredded in accordance with regulations of the St. Mary Parish Solid Waste facility, the cost of disposal shall be the normal tipping fee of $19.00 per ton, as same may be amended from time to time.

b. If the tires are not cut or shredded in accordance with regulations of the St. Mary Parish Solid Waste facility, the cost of cutting, shredding, and disposal shall be:

Tire Description	Tipping Fee
Auto & Light Truck (Less than 17 inch rim)	$ 1.00 each
Large Truck (Greater than 16.5 inch rim) (Includes front tractor tire)	$ 6.00 each
Oversize Tires	
Farm Tractor Tires	$ 20.00 each
Small Aircraft Tires (Less than 16 inch rim)	$ 20.00 each
Large Aircraft Tires (Greater than and equal to 16 inch rim)	$ 25.00 each
Heavy Equipment/Industrial Tires	$200.00 each (or Do Not Accept)

2652

SECTION 2.

All ordinances or parts of ordinances in conflict herewith are hereby repealed.

This ordinance having been offered and read on this 9th day of June, 1993; having been published in accordance with law; and having been heard in a public hearing held at Franklin, Louisiana on the 14th day of July, 1993; was adopted by the following vote on the 14th day of July, 1993.

AYES: Lionel Metz, Paul Naquin, H. A. Louviere, Scott Ramsey, Robert Ayres, Dr. Tim Tregle, Larry Besse, Steve Bierhorst and Albert Foulcard.

NAYS: None.

ABSENT: William Cefalu and Henry Steckler.

APPROVED:

Albert Foulcard

ALBERT FOULCARD, CHAIRMAN
ST. MARY PARISH COUNCIL

ATTEST:

Kimberly W. Pusateri

KIMBERLY W. PUSATERI, CLERK
ST. MARY PARISH COUNCIL

This Ordinance was submitted to the President of St. Mary Parish on this the 16th day of July, 1993 at the hour of 2:05 p.m.

APPROVED:

Oray P. Rogers

ORAY P. ROGERS, PRESIDENT
ST. MARY PARISH

This Ordinance was returned to the Clerk of the Council on this the 16th day of July, 1993 at the hour of 2:26 p.m.

Exhibit 23

Airspace and Borrow Soil Adequacy Volume Calculations and GS-GCL & GCL Equivalency Calculations

Airspace and Borrow Soil Adequacy Volume Calculations

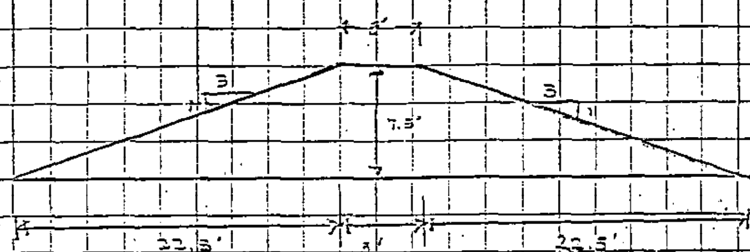
RNER
NMENTAL

CONSULTING ENGINEERS AND SCIENTISTS
7918 Wrenwood Blvd, Suite C
Baton Rouge, Louisiana 70809
PHONE (225) 926-4300
FAX (225) 926-4360

CLIENT NAME: PENSCO	SHEET NO. 1 OF 3
PROJECT TITLE: ST. MARY PARISH LANDFILL, BERWICK, LA	
SUBJECT: AIRSPACE AND BORROW SOIL ADEQUACY	
PROJECT NO.: PEN-001	CALCULATED BY: NH · DATE: 9/18/00 · CHECKED BY: PW · DATE: 9/21/00

PURPOSE: 1) DETERMINE TOTAL AND AIRSPACE VOLUMES
2) APPROXIMATE THE AMOUNT OF SOIL NEEDED TO CONSTRUCT BERMS AND FOR SOIL COVER IN THE WASTE CELLS
3) APPROXIMATE THE AMOUNT OF SOIL AVAILABLE AT THE BORROW AREA FOR THESE PURPOSES

SOLUTION: ALL SLOPES ON THE OUTSIDE OF THE BERMS ARE 3H:1V. INSIDE SLOPES ARE 3H:1V ALSO. THE CREST WIDTH OF BERMS IS 5' ALL THE WAY AROUND THE CELL. THE LENGTH OF THE BERM IS APPROXIMATELY 6140'. THE HEIGHT OF THE BERM IS 7.5'



AREA = (1/2)(22.5')(7.5')(2) + 5'(7.5')
= 168.75 + 37.5
= 206.25 FT^2

VOLUME = AREA x LENGTH
= 206.25 FT^2 (6140')
= 1266375 FT^3
= **46902.8 YD^3**

[...]RNER
[...]NMENTAL
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CLIENT NAME	PENSCO			SHEET NO. 2	OF 3
PROJECT TITLE	ST. MARY PARISH LANDFILL; BERWICK, LA				
SUBJECT	AIRSPACE AND BORROW SOIL ADEQUACY				
PROJECT NO. PEN-00 1	CALCULATED BY: NH	DATE 9/13/00	CHECKED BY: NWF	DATE 9/21/00	

TOTAL VOLUME FOR BERMS = 46903 YD^3
TOTAL VOLUME FOR ENGINEERED FILL BOTTOM CONSTRUCTION = 193600 YD^3
TOTAL VOLUME FOR COVER = 4174642 YD^3

TOTAL VOLUME NEEDED:

46993 YD^3 + 4174642 (0.17) + 193600 = 950192 YD^3

COVER SOIL VOLUMES ARE ASSUMED TO BE 17% OF TOTAL VOLUME BASED ON INDUSTRY STANDARDS. AIRSPACE = 83% = 4174642 (0.83)
= 3418950 YD^3

SOIL AVAILABLE FROM SITE EXCAVATION:

TOTAL = 175332 YD^3
ONLY ABOUT 70% WILL BE USABLE ON-SITE. APPROXIMATELY 30% OF THE EXCAVATED SOILS WILL CONTAIN ROOTS, ETC. AND MAY NOT BE ADEQUATE FOR USE.

∴ USABLE SOIL FROM SITE EXCAVATION = (0.70)(175332 YD^3)
= 122732.4 YD^3

SOIL VOLUME ADEQUACY:

SOIL AVAILABLE − SOIL NEEDED

122732 − 950192 = −827460 YD^3

827460 YD^3 MORE SOIL IS NEEDED.

SOIL NEEDED FOR OPERATIONAL COVER FOR CELL 3 & 3A

AREA OF CELL 3 & 3A = 2188000 FT^2

FOR 2' COMPACTED INTERIM COVER 2188000 (2) = 4376000 FT^3

= 162075 YD^3

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CLIENT NAME	PENSCO			SHEET NO. 3	OF 3
PROJECT TITLE	ST. MARY PARISH LANDFILL, BERWICK, LA				
SUBJECT	AIRSPACE AND BORROW SOIL ADEQUACY				
PROJECT NO. PEN-001	CALCULATED BY NH	DATE 9/18/00	CHECKED BY HW	DATE 9/21/00	

TOTAL SOIL AVAILABLE AT BORROW
(APPROXIMATELY 7 MILES FROM SITE)

26 ACRES OF SOIL 35' DEPTH IS AVAILABLE AT BORROW

26 ACRES = 1132560 FT^2

1132560 (35) = 39639600 FT^3

= 1,468,133 YD^3

950192 YD^3 (BERMS, BOTTOM CONSTRUCTION, CELL IV COVER SOILS)
-122733.4 YD^3 (EXCAVATION)
162075 YD^3 (2' COMPACTED INTERIM COVER, CELL 3 & 3A)
989534 YD^3 SOIL NEEDED

SOIL AVAILABLE = 1468133 YD^3
SOIL NEEDED = 989,534 YD^3
SOIL LEFT TO COMPLETE CELL 3 AND 3A = 478,600 YD^3

AT CURRENT TIME, THERE IS A TOTAL VOLUME OF
1.3 MILLION YD^3 LEFT TO FILL IN CELLS 3 AND 3A.
APPROX 17% OF THIS VOLUME WILL BE OCCUPIED BY SOIL
THIS WILL BE APPROX. 221,000 YD^3

CONCLUSION: THERE WILL BE MORE THAN ENOUGH SOIL IN THE BORROW TO MEET THE NEEDS OF THE LANDFILL.

478,600 - 221000 = 257,600 YD^3
(LEFT OVER AFTER CONSTRUCTION)

Volume totals (...)

Site Volume Table: Unadjusted

```
                 Cut                Fill              Net
                cu.yds             cu.yds            cu.yds       Method
==================================================================
======

Site: Pensco vol
  Stratum: cell 4 to 50 ft  cell 4 btm  cell 4 w 50 ft top
                      0          3837466          3837466 (F) Comp
osite
  Stratum: cell 4 to 36 ft  cell 4 btm  cell 4 w 36 ft top
                      0          2910537          2910537 (F) Comp
osite
  Stratum: cell 4 to 20 ft  cell 4 btm  cell 4 w 20 ft top
                      0          1842083          1842083 (F) Comp
osite
  Stratum: cell 4 phase ii  cell 4 phase ii btm  cell 4 phase ii t
op
                      0          1117105          1117105 (F) Comp
osite
  Stratum: cell 4 & pig 50  cell 4 & pig btm 50  cell 4 & pig top
50
                      0          4174642          4174642 (F) Comp
osite
                      0          4107799          4107799 (F) Grid

  Stratum: cell 4 & pig 36  cell 4 & pig btm 36  cell 4 & pig top
36
                      0          3050244          3050244 (F) Comp
osite
                      0          3049773          3049773 (F) Grid

  Stratum: cell 4 & pig 20  cell 4 & pig btm 20  cell 4 & pig top
20
                      0          1875979          1875979 (F) Comp
osite
  Stratum: piggyback to 20  piggyback btm 20  piggyback top 20
                      0            35415            35415 (F) Comp
osite
  Stratum: cell 4 excavation  cell 4 excav top  cell 4 btm
                 175332                0          175332 (C) Comp
osite
```

GS-GCL & GCL Equivalency

TURNER ENVIRONMENTAL
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CLIENT NAME	PENSCO	SHEET NO. 1 OF 1
PROJECT TITLE	ST. MARY PARISH LANDFILL, BERWICK, LA	
SUBJECT	GS - GCL EQUIVALENCY	
PROJECT NO. TEN-001	CALCULATED BY NH, DATE 8/24/00	CHECKED BY TS, DATE 10/13/00

PROBLEM: SHOW THAT A GCL W/ A GM BACKING PROVIDES EQUIVALENCY OR BETTER PERFORMANCE THAN 3 FT OF COMPACTED CLAY W/ REGARD TO WATERFLUX

PROPERTIES OF MATERIALS: $K = 4 \times 10^{-12}$ cm/s FOR GUNDSEAL GCL W/ 60 MIL HDPE GM
$K = 1 \times 10^{-7}$ cm/s FOR COMPACTED CLAY
THICKNESS OF GUNDSEAL = 1/6" = 0.4233 cm
THICKNESS OF COMPACTED CLAY = 3' = 91.44 cm
HYDRAULIC HEAD = 1' = 30.48 cm

SOLUTION: WATERFLUX CALCULATIONS:

$V = K \frac{H+T}{T}$ WHERE: K = HYDRAULIC CONDUCTIVITY OF MATERIAL
H = DEPTH OF LIQUID PONDED ON LINER
T = THICKNESS OF LINER
V = WATERFLUX

FOR GCL: $V_{GCL} = 4 \times 10^{-12} \times \frac{30.48 + 0.4233}{0.4233}$

$\underline{V_{GCL} = 2.92 \times 10^{-10} \text{ cm/s}}$

FOR 3' OF COMPACTED CLAY: $V_{CCL} = 1 \times 10^{-7} \times \frac{30.48 + 91.44}{91.44}$

$\underline{V_{CCL} = 1.33 \times 10^{-7} \text{ cm/s}}$

RATIO OF WATERFLUX: $\frac{V_{GCL}}{V_{CCL}} = \frac{2.92 \times 10^{-10}}{1.33 \times 10^{-7}} = \underline{2.195 \times 10^{-3}}$

$2.195 \times 10^{-3} < 1.0$

RESULTS: GUNDSEAL GCL IS A BETTER PERFORMER THAN 3 FT OF COMPACTED CLAY W/ REGARD TO WATERFLUX.

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PEMSCO					
PROJECT TITLE	ST Mary Parish Landfill				
SUBJECT	GCL Equivalency				
PROJECT NO. PEM-001	CALCULATED BY TSS	DATE 2/1/01	CHECKED BY JNV	DATE 2/1/01	

Prove i show that a GCL provides equivalency or better performance than 2 ft of compacted clay w/regard to water flow

Properties of Materials: $k = 5 \times 10^{-9}$ cm/s for GCL
$k = 1 \times 10^{-7}$ cm/s for CCL
Thickness of GCL = .7 cm
Thickness of CCL = 60.96 cm
Hydraulic head = 2 cm (due to a composite drainage layer)

Solution:

$$\text{Water flux} = Q/A = k \cdot i$$

$$\text{where } i = \frac{\text{head} + \text{thickness}}{\text{thickness}}$$

$$\text{Water flux for CCL} = Q/A = 1 \times 10^{-7}\ \text{cm/s} \left(\frac{2 + 60.96}{60.96}\right)$$

$$= 1.03 \times 10^{-7}\ \text{cm}^3/\text{cm}^2/\text{sec}$$

$$= \underline{\underline{95\ \text{gal/acre/day}}}$$

$$\text{Water Flux for GCL} = Q/A = 5 \times 10^{-9}\ \text{cm/s} \left(\frac{2 + 0.7}{0.7}\right) = 1.93 \times 10^{-8}\ \text{cm}^3/\text{cm}^2/\text{sec}$$

$$= 17\ \text{gal/acre/day}$$

Water Flux GCL < Water Flux CCL

17 gal/acre/day < 95 gal/acre/day

TECHNICAL EQUIVALENCY OF GUNDSEAL TO COMPACTED CLAY

Sec. Exp
S21.F.4.6

Since their introduction in 1986 as barrier systems for waste containment sites, geosynthetic clay liners have been installed in a wide variety of landfill, wastewater treatment, and secondary containment systems. With the increasing interest in the use of GCLs as part of a liner system, both state and federal regulatory agencies have been bombarded with questions by landfill owners, operators, and design consultants as to the position of these agencies on the use of GCLs in waste containment systems.

Often, the standard answer received by the design engineer or owner/operator is that they must show that the GCL is equal to a specified thickness of clay. A review of both compacted clays and geosynthetic clay liners reveals that there is no way that they can be equal. In other words, a 1/6 inch GCL is not equal to two feet of clay. However, the performance of a GCL can be considered equivalent to the performance of a clay liner. Koerner and Daniel (1993) and Daniel (1993) present data in papers regarding the equivalent assessment of GCLs compared to compacted clay liners (CCLs). Table I presents the potential equivalency issue presented in Koerner and Daniel's paper. As is indicated in the table, there are three major categories involved with comparing compacted clay liners and geosynthetic clay liners. These categories are hydraulic issues, physical/mechanical issues, and construction issues. Table II presents the technical equivalency assessment for GundSeal installed beneath a geomembrane in landfill and surface impoundment liner systems. You will note that there are only two areas where GundSeal is probably not equivalent to a compacted clay line. These areas are chemical absorption capacity under the hydraulic issue and puncture resistance under the construction issue.

Equivalency to compacted clay cannot be demonstrated for GCLs with regard to chemical absorption capacity. However, this question is mute if a geomembrane/geosynthetic clay liner composite liner system has be4en properly installed. The absorption by GundSeal may be adequate to very low water flux. In the long term, the absorption capacity for all liners may eventually be exhausted. If the composite is the primary liner of a double liner system, the leak detection system will handle the liquid, and absorption is not relevant. Therefore, only when a GCL is used by itself can real concern be expressed for chemical absorption capacity. Even then, site specific conditions will be very important.

The puncture resistance of two feet of compacted clay is obviously much higher than the puncture resistance of a thin GCL. However, careful CQC/CQA procedures are able to address the potential puncture problem. As noted in Table II, the advantages of GCLs over compacted clay more than offset its vulnerability to puncture.

In Appendix 1, water flux calculations have been prepared for both GundSeal and compacted clay liner. From these calculations, it is quite evident that the GundSeal geosynthetic clay liner performs much better that a compacted clay liner. This type of analysis and comparison can be performed for all of the items listed in Table I. A detailed discussion is presented by Koerner and Daniel (1993) for all of these items.

REFERENCES

Daniel D.E. (1993) "Geosynthetic Clay Liners (GCLs) in Landfill Covers." Proc. *SWANA Conf.*, San Jose, CA.

Koerner, R.M. and Daniel, D.E. (1993) "Technical Equivalency Assessment of GCLs to CCLs. "Proc. Seventh Annual GRI Seminar, Geosynthetics Research Institute, Philadelphia, PA.

APPENDIX 1

Water Flux Calculations

Water flux is defined as the volume of flow across a unit area in a unit time. The steady downward flux of water (v) through an individual layer of porous material with zero water pressure at the base of the layer is defined from Darcy's law as

$$V = K \frac{H + T}{T} \quad \text{where}$$

K = hydraulic conductivity of material
H = depth of liquid ponded on the liner
T = thickness of the liner

The above equation is valid for flow through the bentonite component of Gundseal. Since Gundseal contains a geomembrane, water flux is controlled by water vapor diffusion through the geomembrane backing. However, in performing an equivalency analysis to compacted clay and in computation of water flux, the geomembrane backing should be considered by the design engineer. The simplest way to perform this analysis is to adjust the hydraulic conductivity of Gundseal to include the geomembrane. This simplification is not indicative of the actual flow considerations since water flows through a geomembrane by diffusion and Darcy's law does not apply to diffusion. However, by making this simplifying assumption, an engineer can obtain an estimate of water flux for Gundseal.

The water flux equation applies to Gundseal or a compacted clay liner alone and does not apply to composite liners involving one or more separate geomembrane components.

For Gundseal the water flux for a site where H = 1' (30.48 cm) is calculated as follows:

$$K = 4 \times 10^{-12} \text{ cm/sec} \qquad T = 1/6'' = 0.4233 \text{ cm}$$

$$V_{GCL} = (4 \times 10^{-12} \text{ cm/sec}) \times \frac{30.48 \text{ cm} + 0.4233 \text{ cm}}{0.42233 \text{ cm}}$$

$$V_{GCL} = 2.92 \times 10^{-10} \text{ cm/sec}$$

For two (2) feet (60.96 cm) of compacted clay where

$$K = 1 \times 10^{-7} \text{ cm/sec}$$

$$V_{CCL} = (1 \times 10^{-7} \text{ cm/sec}) \times \frac{30.48 \text{ cm} + 60.96 \text{ cm}}{60.96 \text{ cm}}$$

$$V_{CCL} = 1.5 \times 10^{-7} \text{ cm/sec}$$

[illegible]e flux ratio for water, F_w is defined as the flux through the GCL divided by the flux [illegible]ugh the compacted clay liner (CCL).

$$F_w = \frac{V_{GCL}}{V_{CCL}} = \frac{2.92 \times 10^{-10}\ cm/sec}{1.5 \times 10^{-7}\ cm/sec} = 1.95 \times 10^{-3}$$

Since the flux ratio is ≤ 1 ($1.95 \times 10^{-3} < 1$), then Gundseal is more than equivalent to a CCL in terms of steady water flux.

Alternatively, the engineer can assume the water flux (V) through a CCL and Gundseal are equal

$$V_{GCL} = V_{CCL}$$

and compute the required hydraulic conductivity for Gundseal using the following equation:

$$(K_{GCL})\,req = K_{CCL} \times \frac{T_{GCL}}{T_{CCL}} \times \frac{H + T_{CCL}}{H + T_{GCL}}$$

For the previous example

$$(K_{GCL})\,req = (1 \times 10^{-7}\ cm/sec) \times \frac{0.4233\ cm}{60.96\ cm} \times \frac{30.48\ cm + 60.96\ cm}{30.48\ cm + 0.4233\ cm}$$

$$= 2.05 \times 10^{-9}\ cm/sec$$

$K_{Gundseal} = 4.2 \times 10^{-12}\ cm/sec \leq 2.05 \times 10^{-9}$

Therefore, using either method, Gundseal is more than equivalent to two (2) feet of compacted clay when considering the water flux through a CCL.

TABLE 1A

Potential Equivalency Issues For Geosynthetic Clay Liners (GCLs) vs. Compacted Clay Liners (CCLs)

Category	Criterion for Evaluation	Possibly Relevant for: Liners	Possibly Relevant for: Covers
Hydraulic Issues	Steady Flux of Water	X	X
	Steady Solute Flux	X	
	Chemical Adsorption Capacity	X	
	Breakout Time:		
	- Water	X	X
	- Solute	X	
	Production of Consolidation Water	X	X
	Permeability to Gas	X	X
Physical/ Mechanical Issues	Freeze/Thaw	X[1]	X
	Wet/Dry		X
	Total Settlement	X[2]	X
	Differential Settlement	X[2]	X
	Slope Stability	X[3]	X
	Erosion		X
	Bearing Capacity	X	X
Construction Issues	Puncture Resistance	X	X
	Subgrade Condition	X	X
	Ease of Placement	X	X
	Speed of Construction	X	X
	Availability of Materials	X	X
	Requirements for Water	X	X
	Air Pollution Effects	X	X
	Weather Constraints	X	X
	Quality Assurance	X	X

[1]Relevant only until liner is covered sufficiently to prevent freezing
[2]Settlement of liners usually of concern only in certain circumstances, e.g., vertical expansions
[3]Stability of liner may not be relevant after filling if no permanent slope remains

[A]Daniel (1993), "Geosynthetic Clay Liners (GCLs) in Landfill Covers", Presented at Thirty First Annual Solid Waste Exposition, Solid Waste Association of North America, San Jose, California, August 2-5, 1993.

TABLE II*

Technical Equivalency Assessment for Gundseal Installed Beneath Geomembranes in Landfills and Surface Impoundements

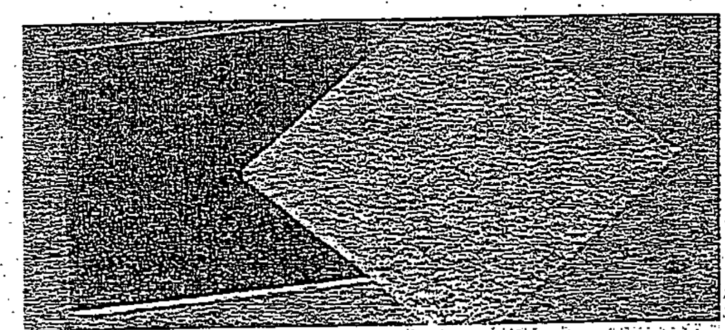
Category	Criterion for Evaluation	Gundseal is Superior	Gundseal is Equivalent	Gundseal is probably not Equivalent
Hydraulic Issues	Steady flux of water		X	
	Steady solute flux		X	
	Chemical adsorption capacity			X
	Breakout time			
	Water	X		
	Solute	X		
	Horiz. flow in seams or lifts		X	
	Horiz. flow beneath geomembrane	X		
	Generation of consolidation water	X		
Physical/ Mechanical Issues	Freeze/thaw behavior	X		
	Total settlement		X	
	Differential settlement	X		
	Slope stability		X[1]	
	Bearing capacity		X[1]	
Construction Issues	Puncture resistance			X
	Subgrade condition		X	
	Ease of placement	X		
	Speed of construction	X		
	Availability of materials	X		
	Requirements for water	X		
	Air pollution concerns	X		
	Weather constraints	X		
	Quality assurance considerations		X	

[1] Equivalent when installed with geomembrane backing facing downward against subgrade soils and covered with another geomembrane.

* Table adapted from "Technical Equivalency Assessment of GCLs to CCLs, Koerner and Daniel (1993); Proceedings of the 7th GRI Seminar, Geosynthetic Liners Systems: Innovations, Concerns, and Design, Drexel University, Philadelphia, PA, pp 255-275.

GSE GUNDSEAL PRODUCT OVERVIEW

The GundSeal GCL is the most hydraulically advanced lining product available, over 1,000 times less permeable than conventional fabric encased GCLs. The product combines a 12 mil to 80 mil (0.3 mm to 2.0 mm) HDPE geomembrane with the swelling and sealing ability of high grade sodium bentonite. The bentonite is attached to the geomembrane using a non-toxic non-polluting adhesive. Together, this double barrier system acts as a self sealing composite liner.



GundSeal is used as an effective and cost efficient replacement for compacted clay liners (CCLs) and has the hydraulic equivalence of more than three feet (0.9 m) of compacted clay. The product can be installed with either the bentonite side facing downward, in contact with subgrade soils, or with the geomembrane side facing up with a separate overlying geomembrane. The geomembrane backing of GundSeal can either be smooth surfaced or textured, depending on project slopes and stability requirements.

Given the technical nature of the product, special design considerations must be incorporated into each product application with GundSeal. Exceptional performance makes the GundSeal GCL ideal for landfill liners/caps, solid/liquid containment impoundments, secondary containment, and many other non-exposed liner or cap projects. Compatibility of the bentonite coating with the project leachate must be evaluated for each application.

General benefits of the GundSeal GCL include:

◊ GundSeal is simply unrolled, no heavy equipment needed.
◊ Much less permeable than compacted clay liners or fabric encased GCLs.
◊ True intimate contact exists between the bentonite and overlying/underlying geomembranes.
◊ Can be installed to replace compacted clay requirements resulting in air space savings and reduced construction costs.
◊ Can be used as a one product composite liner (geomembrane/clay).
◊ GundSeal is not affected by freeze/thaw cycles and wet/dry cycles in comparison to compacted clay.
◊ The geomembrane backing of GundSeal effectively resists bentonite desiccation cracking and root penetration.

GSE GundSeal Product Applications

The GundSeal GCL can be manufactured with a geomembrane backing ranging from 0.3 mm to 2.0 mm (12 mil to 80 mil), smooth or textured HDPE. The material is suitable for most environmental lining projects, including landfill bottom liners or caps, solid/liquid waste impoundments, secondary containment, and many other non-exposed applications. Given the various geomembrane manufacturing options, GundSeal products and applications are generally divided into three general product categories including (1) replacement for a compacted clay liner (CCL) on gently sloping applications, (2) replacement for a CCL on steep sloping applications, (3) utililzed as a one product composite (geomembrane/clay) liner.

1. Replacement for a CCL: GundSeal 0.3/0.5 mm (12/20 mil) HD smooth geomembrane. Gently sloping applications, typically less than 11°.

   Application: Replacement for all or part of a compacted clay liner (CCL).

   Installation: Deployed by itself, bentonite side down, when the design specifies a CCL/GCL only (Fig. 1). Alternately, in gently sloping composite geomembrane/clay applications, deployed bentonite side up with a separate overlying geomembrane, typically 1.5/2.0 mm smooth (Fig. 2).

   Product Considerations: Engineering preference and design geomembrane requirements differentiate geomembrane backing selection.

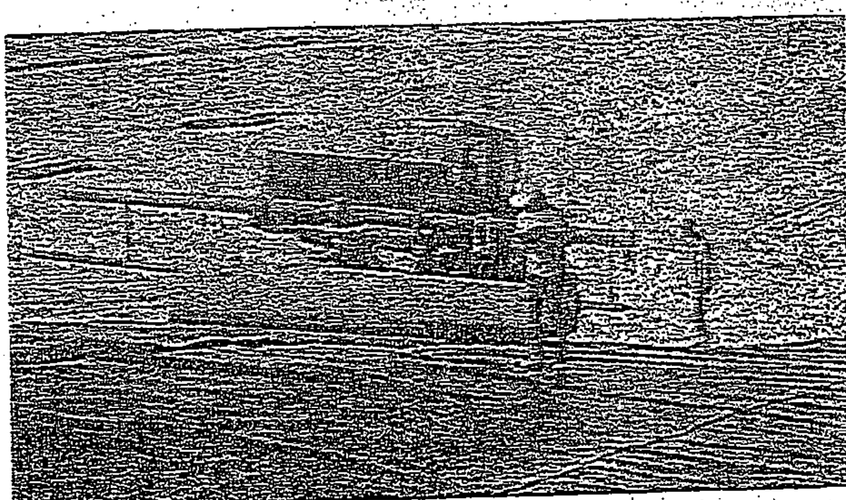


Fig. 1. GundSeal deployed HDPE geomembrane side up (bentonite side down) as a replacement for a CCL

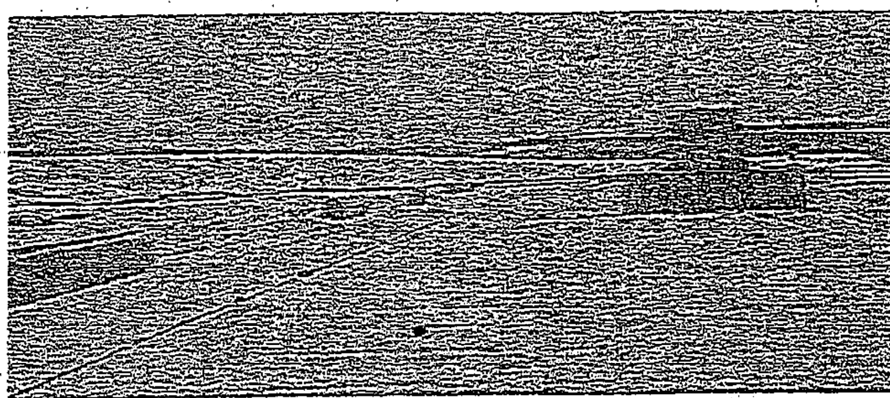


Fig. 2. GundSeal 0.5 mm HD geomembrane backing deployed bentonite side up as a replacement for a CCL in a composite bottom liner system.

2. REPLACEMENT FOR A CCL: GUNDSEAL 0.75/1.0 MM (30/40 MIL) HD TEXTURED GEOMEMBRANE. Sloping GCL applications typically less than 26°.

Application: Replacement for all or part of a CCL.

Installation: Deployed by itself, bentonite side down, when the design includes a GCL only on slopes up to 18° under low normal loads.

Alternately, in composite liner/cap applications, deployed bentonite side up with a separate overlying textured geomembrane (typically 1.5/2.0 mm textured). Typical installation for designs that encase bentonite between two geomembranes, keeping the bentonite dry for long term slope stability. This design effectively increases applications to slopes up to 26° under high normal loads, such as in bottom composite liner systems (Fig. 3).

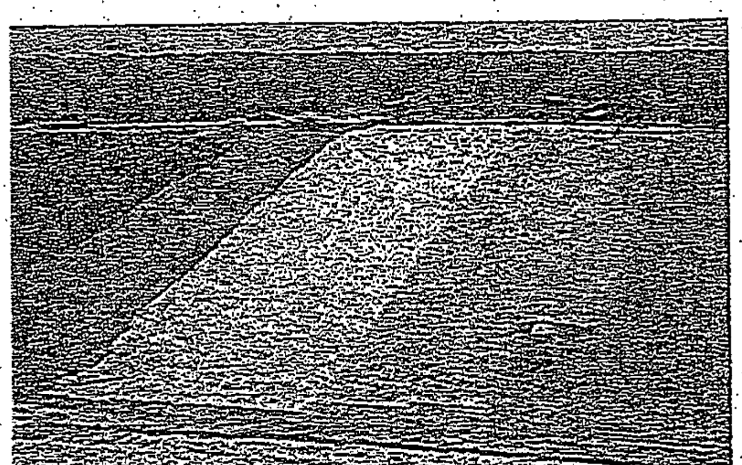


Fig. 3. GundSeal 0.75 mm HD Textured geomembrane backing deployed bentonite side up with an overlying HD White surfaced geomembrane.

3. ONE PRODUCT COMPOSITE LINER: GUNDSEAL 1.5/2.0 MM (60/80 MIL) SMOOTH/TEXTURED HDPE GEOMEMBRANE BACKING. Flat or sloping composite liner/cap applications typically less than 18°.

   Application: One product composite liner. GundSeal geomembrane and bentonite layer replace a composite liner/cap design, including all or part of the CCL. Product is manufactured with the specified geomembrane.

   Installation: Deployed by itself, bentonite side down against the subgrade soil. Seams are simply overlapped for effective sealing. Additional option of bentonite free geomembrane edges for welding the geomembrane seams between GundSeal panels (Fig. 4).

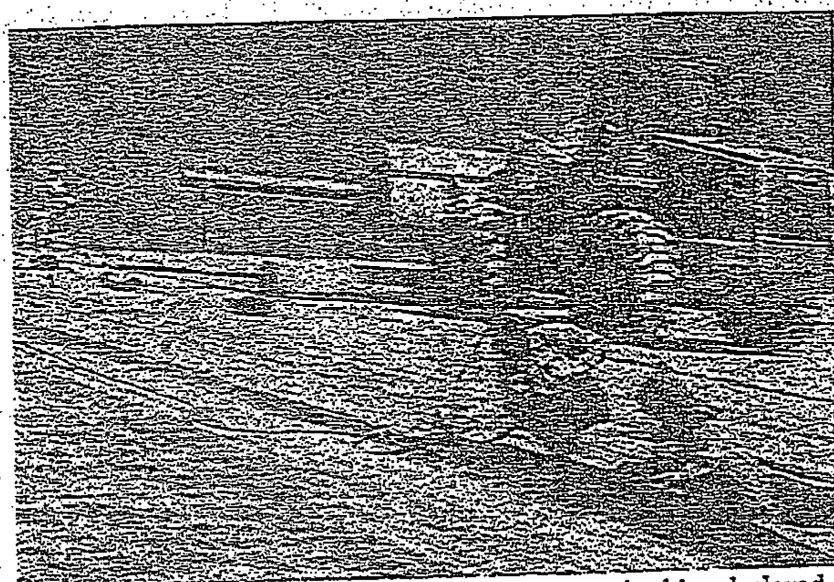


Fig. 4. GundSeal 1.5 mm HD Textured geomembrane backing deployed as a one product composite (geomembrane/clay) bottom liner.

GSE GUNDSEAL PERFORMANCE BENEFITS

GundSeal® is the only geosynthetic clay liner (GCL) that provides the high swelling and sealing potential of bentonite clay and the low permeability of a geomembrane. GundSeal consists of one pound per square foot of high quality sodium bentonite adhered to a polyethylene geomembrane. This composite design lets the installer conveniently roll out a blanket of clay, competitively replacing or supplementing compacted clay that is required for liners and cap systems. The standard geomembrane backings for GundSeal are 20 mil (0.5 mm) smooth HDPE and 30 mil (0.75 mm) textured. However, the backing can range up to 80 mils (2.0 mm) in thickness and can be textured for improved slope stability. The rolls are 17.5 feet (5.3 m) wide and vary in length from 150 feet to 200 feet (45 m to 60 m). All GundSeal rolls weigh approximately 4,200 lb. (1,900 kg).

PERMEABILITY

GundSeal is typically deployed in a liner system with its protective geomembrane backing facing downward against the subgrade or drainage layer and a separate overlying geomembrane seamed over the top of the bentonite. By combining the swelling and sealing of sodium bentonite with an essentially impermeable geomembrane, this forms a composite liner system which surpasses conventional liner systems developed with either compacted clay or a fabric encased GCLs. With a permeability of less than 4×10^{-14} m/sec, GundSeal is more than 1,000 times less permeable than fabric encased GCLs. This extremely low permeability allows regulators and engineers to replace all or part of compacted clay requirements for landfill liner and cap systems.

COMPOSITE ACTION

The fact that there is no geotextile covering the bentonite to prevent intimate contact with the overlying geomembrane allows the bentonite and upper geomembrane to have the kind of intimate contact unavailable with either compacted clays or fabric encased geosynthetic clay liners, enabling construction of ideal composite liner systems.

SEAM INTEGRITY

The intimate contact of GundSeal allows the seams to be simply overlapped with confidence that integrity of permeability will be maintained. GundSeal can also be placed bentonite side down, either overlapped as shown or extrusion welded, making it the most versatile GCL on the market. For bentonite side down applications, a thin fabric coating can be adhered to the bentonite face during manufacturing if desired.

As well as simple overlapped seams, the seams between GundSeal panels can also be welded making GundSeal a one product composite liner.

SHEAR STRENGTH

When GundSeal is installed with the geomembrane facing downward and an overlying geomembrane covering the bentonite, the dry shear strength of the bentonite may be used in slope stability analyses. Test results have indicated that the excellent composite action developed between the overlying geomembrane and the bentonite prohibits the bentonite from becoming hydrated. In addition, the geomembrane backing of GundSeal prevents the bentonite from "sucking up" moisture from the subgrade soils as occurs with fabric encased GCLs. Therefore, the dry shear strength of the bentonite in GundSeal can be utilized for design purposes.

EASE OF INSTALLATION

On top of its outstanding engineering characteristics, another primary advantage of the GundSeal geosynthetic clay liner is that with its geomembrane backing, it is easy to install. GundSeal can be dragged or pulled into position without any fear of dislodging the bentonite. For deployment of GundSeal bentonite side down, the material is unrolled into position using a spreader bar and front end loader, similar to installation of geomembranes.

IMPROVED SOIL LINER CONSTRUCTION

Geosynthetic Clay Liners (GCLs) are uniform, factory produced blankets of bentonite clay which are deployed without heavy equipment and used to replace or supplement traditional compacted clay liners (CCLs). GCLs are not affected by many of the difficulties associated with compacting a clay liner. They are deployed dry and are, therefore, not ruined by desiccation. In service as soil liners, they have lower permeability than compacted clay, are not damaged by freeze/thaw or wet/dry cycles, and conform to differential settlement with flexibility and self healing.

In addition to many performance advantages, geosynthetic clay liners provide owners, operators, and municipalities considerable economic advantages through cost savings and revenue potential over compacted clay liners.

ADDITIONAL BENEFITS OF THE GSE GUNDSEAL GCL

◊ Product is simply unrolled, no additional heavy equipment needed.
◊ Confined bentonite has much lower permeability than compacted clay.
◊ Unlike compacted clay, swelling capability provides true intimate contact for composite liner/cap systems.
◊ GundSeal is less affected by freeze/thaw cycles than compacted clay liners.
◊ Given the geomembrane backing, GundSeal is not susceptible to desiccation cracking or root penetration.

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TYPICAL QUESTIONS AND ANSWERS
GSE GUNDSEAL® GEOSYNTHETIC CLAY LINER

Q. What is GundSeal?

A. GundSeal is a bentonite clay/polyethylene geomembrane composite liner for one step deployment as a replacement for all or part of a compacted clay liner (CCL). The product combines a low permeability 12 mil to 80 mil (0.3 mm to 2.0 mm) polyethylene geomembrane with 1 lb/sq ft (4.9 kg/sq m) loading of high grade sodium bentonite using a non-toxic non polluting adhesive. Together, they act as a low permeability self sealing liner.

Q. How is GundSeal different from other GCLs?

A. By definition, a geosynthetic clay liner is defined as a factory manufactured geosynthetic hydraulic barrier consisting of clay supported by geosynthetic carriers, such as geomembranes or geotextiles. GundSeal, referred to as a *geomembrane supported GCL* attaches the bentonite directly to a geomembrane using a non-toxic adhesive. Other GCLs, referred to as *fabric encased GCLs*, encapsulate the bentonite between geotextiles.

Q. What applications are suitable for GundSeal?

A. The GundSeal GCL can be used for most waste containment applications suitable for a bentonite based material as a replacement for all or part of a compacted clay liner (CCL). This includes landfill liners and caps, secondary containment, impoundments and lagoons. GundSeal should not be used for exposed applications given that the bentonite requires a confining pressure to perform effectively.

Q. How are GundSeal rolls packaged and handled?

A. The GundSeal rolls are typically 17.5 ft (5.3 m) wide and approximately 150 ft to 200 ft (45 m to 60 m) long, dependent upon the geomembrane backing thickness, and approximately 4200 lb. (1900 kg). The material is rolled on continuous cardboard cores and protected with an outer wrap of HDPE geomembrane and finally stretch wrapped with visquine. The rolls are handled with loading straps supplied with each roll

Q. How is the material installed?

A. GundSeal is simply unrolled in place similar to installing rolls of carpet. The rolls are typically deployed with the bentonite side up, liner side down, with a separate overlying geomembrane as a replacement for all or part of a CCL. Alternately, the material can be deployed with the bentonite facing down, geomembrane side up, as a one product composite (geomembrane/clay) liner.

Q. How are GundSeal seams made?

A. The typical seams between installed panels are made by simply overlapping the material. The lengthwise seams are typically overlapped a minimum 6 inches (150 mm) and the widthwise seams are overlapped 1 ft (300 mm).

Q. What is difference between sodium bentonite and calcium bentonite?
A. Bentonite is a montmorillonite clay formed from altered volcanic ash originally deposited in prehistoric marine environments. Sodium bentonite was formed in a salt water marine environment and calcium bentonite formed in a fresh water environment. Bentonite is unique in that it has the ability to absorb water and expand up to 15 times its original weight for sodium bentonite and approximately 3 times its original weight for calcium bentonite. With this absorption of water and expansion, the result is a marked decrease in clay hydraulic conductivity well below that of typical clays.

Q. Is GundSeal technically equivalent to a typical compacted clay liner (CCL)?
A. Yes. GundSeal has the hydraulic equivalence to a standard compacted clay liners which range in thickness from 1 ft to 5 ft (0.3 m to 1.5 m) of low permeability soil. Given the low hydraulic conductivity of GundSeal (less than 4×10^{-14} m/sec) compared to a typical CCL (1×10^{-9} m/sec), flow through the GundSeal GCL is more than 100,000 times less than a typical compacted clay.

Q. What is the difference in hydraulic conductivity compared to fabric GCLs?
A. The permeability of typical fabric encased GCLs is that of the bentonite layer, approximately 5×10^{-11} m/sec. Given that the construction of GundSeal includes a geomembrane carrier geosynthetic, this decreases the product permeability to less than 4×10^{-14} m/sec. Therefore, the GundSeal GCL is more than 1,000 times less permeable than the fabric encased GCLs.

Q. What kind of geomembranes can GundSeal be made with?
A. GundSeal is typically manufactured with a HDPE geomembrane ranging in thickness from 12 mil (0.3 mm) up to 80 mil (2.5 mm). The geomembrane can be either smooth surfaced or textured surface depending upon project slopes and stability requirements.

Q. Can GundSeal be used to replace a composite liner (geomembrane/CCL)?
A. Yes. The bentonite clay component of GundSeal can be used to replace all or part of a CCL and the geomembrane backing of GundSeal can be substituted for the required geomembrane.

Q. How is GundSeal affected by wet-dry cycles or freeze-thaw cycles?
A. Unaffected. Extensive research has demonstrated that high purity sodium bentonite, as is used in the GundSeal GCL, is unaffected by wet-dry and freeze thaw cycles.

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Q. Can GundSeal panels be welded together like typical geomembranes?

A. Yes. For applications that require the geomembrane backing of GundSeal to be welded, such as when it is used as a composite liner, the GundSeal geomembrane backings can be welded together at seams. The material is manufactured with protective edge tape which keeps bentonite from being attached to the length wise edges. This tape is removed after installation and just prior to welding which creates a clean edge for fusion or extrusion welding. To replace the bentonite at the seam area, a GundSeal seam strip is positioned under the seam which ensures continuous bentonite under the welded geomembrane seam.

Q. Can GundSeal be used for sloping applications?

A. Yes. For project slopes requiring increased friction resistance and shear strength, GundSeal is manufactured with a textured geomembrane. The textured geomembrane increases friction resistance with the bentonite coating of GundSeal. Additionally, when GundSeal is deployed bentonite side up with a separate overlying geomembrane, this design effectively encases the bentonite coating between two geomembranes which gives the greatest guarantee of long term stability.

Q. Is GundSeal compatible with all leachates and waste streams.

A. No. The compatibility of the bentonite coating of GundSeal with the leachate or waste stream must be evaluated for each application. Sodium bentonite is compatible with many chemicals and compounds. However, the swelling and permeability of sodium bentonite is negatively affected in the presence of liquids containing concentrated salts (such as brines), concentrated organic solutions (such as hydrocarbons), divalent cation concentrations (such as Ca^{++} and Mg^{++}), and strong acids (pH <3) or bases (pH >11).

Q. Can GundSeal be used in applications with liquids that present problems for bentonite compatibility?

A. Project specific. If the bentonite is pre-hydrated with typical water prior to exposure to the harsh liquids, the bentonite may do well and perform long term. However, this must be evaluated on a project specific basis.

Q. Is GundSeal available with different types of bentonite or bentonite loading?

A. Yes. GundSeal is available with a contaminant resistant bentonite for applications which require a bentonite with a compatibility with harsher liquids or leachates. The bentonite content of GundSeal can also be increased up to a loading of about 2 lb/sq ft (9.8 kg/sq m).

TECHNICAL PERFORMANCE SUMMARY: GSE GUNDSEAL GEOMEMBRANE SUPPORTED GCL

The GundSeal geomembrane supported geosynthetic clay liner (GS-GCL) was first manufactured and introduced into the environmental market in 1990. The product manufacturing process and overview of applications are given by Erickson & Anderson (1994) and Pape & Erickson (1995). The finished product consists of approximately 4.9 kg/m^2 (1.0 lb/ft^2) of bentonite attached to a geomembrane using a non-toxic water based adhesive (Fig. 1). A thin 0.75 oz/yd^2 spun-bound geotextile is attached to the bentonite surface to provide additional protection to the bentonite and enhance installation of the product. Depending upon the application and project slopes, the geomembrane backing can include a smooth or textured HDPE or VFPE material ranging in thickness from 0.4 mm (15 mil) to 2.0 mm (80 mil). The product combines an essentially impermeable geomembrane with the swelling and sealing ability of sodium bentonite creating a one product self sealing composite liner (geomembrane/clay).

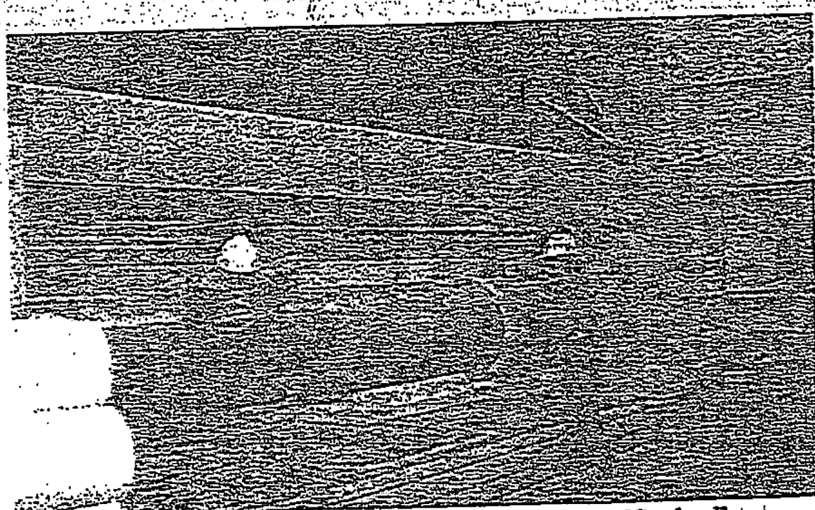

Fig. 1. Winding and packaging of the finished GundSeal rolls.

As with fabric encased GCLs, the product can be utilized in bottom liner and cap applications as a replacement for compacted clay liners (CCLs). When utilized in composite bottom liner or cap applications (geomembrane/GCL), the GS-GCL is typically deployed geomembrane side down, bentonite side up, with a separate overlying geomembrane (Fig. 2). Alternately, the GS-GCL can be deployed bentonite side down, geomembrane side up, when used as a one product replacement for CCLs in cap applications requiring only a CCL (Fig. 3).

Given the geomembrane backing of the product, the performance advantages of the GS-GCL in comparison to CCLs and fabric encased GCLs are described in the following sections.

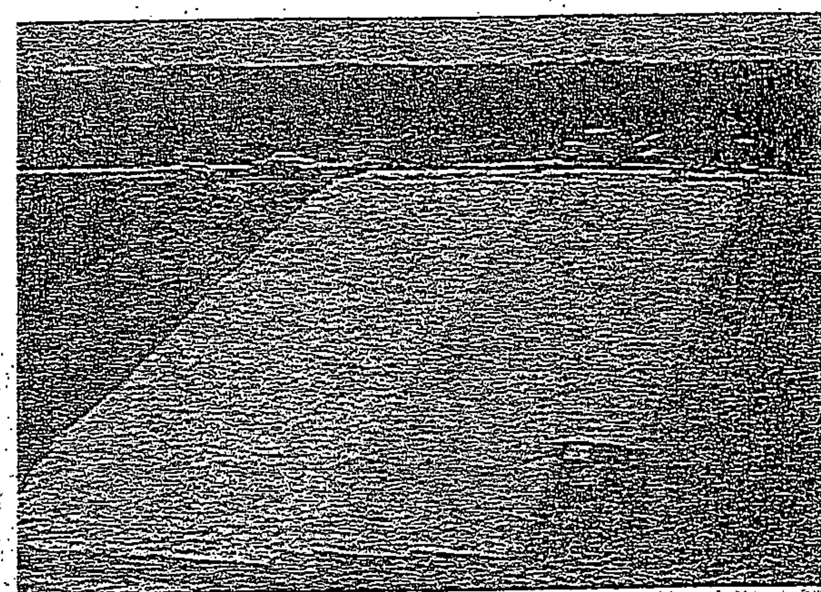

Fig. 2. The GundSeal GS-GCL deployed in a MSW composite bottom liner application with an overlying white surfaced geomembrane.

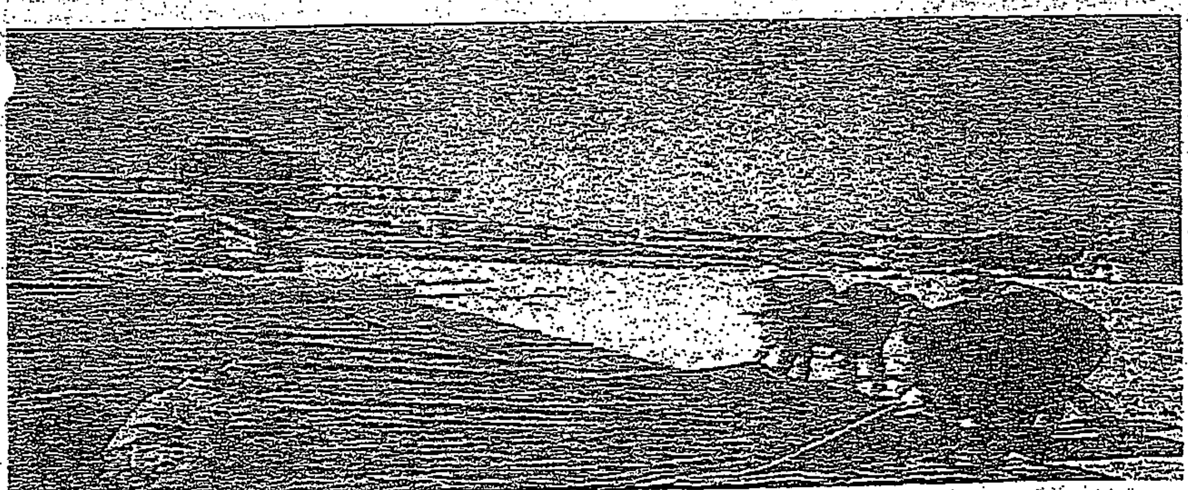

Fig. 3. The GundSeal GS-GCL installed as a replacement for a CCL in a hazardous waste landfill closure.

LOWER PERMEABILITY AND WATER FLUX THROUGH THE GUNDSEAL GS-GCL

With the carrier synthetic being a geomembrane, liquid flux through the GS-GCL is controlled by water vapor diffusion through the geomembrane backing. This derives an effective permeability $<4 \times 10^{-14}$ m/sec and provides the lowest permeability and resistance to flow of any bentonite or clay based product available to the environmental industry.

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When compared to fabric encased GCLs, or bentonite alone, with typical permeability $<5 \times 10^{-11}$ m/sec (Koerner & Daniel, 1995), the GS-GCL derives orders of magnitude (1,000 times) less hydraulic flux through the GCL. The superior resistance to flow and leakage through the GS-GCL has been demonstrated by Estornell & Daniel (1993) and Erickson et al. (1994).

EFFECTIVE COMPOSITE ACTION AND SEAM INTEGRITY

As there are no thick geotextiles covering the bentonite surface of the GS-GCL to interfere with the sealing ability of the bentonite, direct intimate contact exists between the bentonite and overlying and underlying geomembranes. In composite liner or cap applications, this intimate contact results in the most effective composite action and sealing available between a CCL or GCL and a geomembrane (Harpur, 1993, and Estornell & Daniel, 1993).

In regard to sealing at seam areas between adjacent panels of the GS-GCL, the seams are simply overlapped with no additional bentonite or welding of the geomembranes required. The simple overlapped GS-GCL seams, when installed properly, have proven to effectively seal all flow due to the effective composite action between the bentonite and geomembranes (Estornell & Daniel, 1993, and GeoSyntec, 1992).

RESISTANCE TO ROOT PENETRATION AND DESICCATION

Compacted soil liners and fabric encased GCLs utilized in cap applications without adequate overlying protection have been found to be sensitive to desiccation cracking and shrinkage. Upward water transport and plant root water uptake can cause the irreversible formation of cracks in the bentonite or clay liner resulting in potential flow paths through the clay liners (Melchoir, 1997). Protective geomembranes placed over clay liners and fabric encased GCLs can act as effective barriers in minimizing the potential for associated penetrations and cracking in CCL or GCL.

When utilized as a replacement for compacted clay cap applications, the GS-GCL is deployed geomembrane side up with the overlying soil cover placed above the geomembrane (Fig. 2). The geomembrane barrier of the GS-GCL offers a suitable barrier between the overlying cover soil and underlying bentonite whereby minimizing the potential for bentonite desiccation and root penetration through the GCL.

VAPOR BARRIER AND PERFORMANCE ON SLOPES

When utilized in a composite bottom liner or cap application, the GS-GCL is deployed bentonite side up, geomembrane side against the subgrade, with a separate overlying geomembrane (Fig. 2).

The bentonite coating is utilized to replace all or part of the compacted clay layer and the underlying geomembrane backing effectively functions as a vapor barrier between the underlying subgrade and the bentonite.

This installation effectively sandwiches the bentonite between two geomembrane layers with the dry bentonite in direct intimate contact with the upper and lower geomembranes. For any potential breach through the upper or lower membranes, the dry bentonite is positioned to hydrate and expand both horizontally and vertically to seal against potential leakage through the composite liner or cap system.

For relatively flat lying applications, the standard geomembrane backing of the GundSeal GS-GCL is typically 0.4 mm (15 mil) but may be varied to accommodate site specific conditions and design considerations.

Given the low shear strength of hydrated bentonite, one of the primary concerns in using GCLs in containment applications is the stability of the GCL on slopes. When the GS-GCL is deployed with a separate overlying geomembrane on slopes, the dry shear strength properties of the bentonite may be used for design purposes. This triple composite liner (geomembrane/clay/geomembrane) configuration seals the bentonite from moisture from both above and below and presents the greatest assurance of long term performance on slopes. To maximize friction resistance between the adjacent layers, the standard geomembrane backing of the GS-GCL for sloping applications includes a 0.75 mm (30 mil) two sided textured geomembrane.

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Determination of Shear Strength Properties GundSeal Geosynthetic Clay Liner

With the advent of various geosynthetic clay liners on the environmental market, some confusion has developed among consulting engineers and state and federal regulators as to what shear strength should be utilized, in design purposes, for the geosynthetic clay liners. This confusion arises over data presented by the various manufacturers that indicate a scatter of shear strength results.

GSE embarked on a research project to determine which shear strength properties of the bentonite portion of its geosynthetic clay liner, GundSeal, should be used by the design community. This research has been performed by Dr. David E. Daniel, P.E. of the University of Texas at Austin. Dr. Daniel was selected based upon his knowledge of shear strength for soils as well as his knowledge of landfill design criteria.

One of Dr. Daniel's early reports (Daniel 1991) presents the results that he and a graduate student, H. Y. Shan, developed on the three geosynthetic clay liners that were available in the summer of 1991. These test results were performed at a strain rate of 0.0003 mm per minute and at normal stresses ranging from 6.3 psi to 20.1 psi. The failure envelope through the points was determined by a linear regression analysis. The reported results for GundSeal were cohesion of 1.1 psi at an angle of internal friction of 8°. However when the lowest normal stress was plotted with cohesion of 0, angle of internal friction of 17° degrees was obtained.

During the time period that the shear strength tests were being performed on the various GCLs, another graduate student at the University of Texas at Austin, Paula Estornell, was working on her master's thesis entitled "Bench Scale Hydraulic Conductivity Tests of Bentonitic Blanket Materials For Liner and Cover Systems." She and Dr. Daniel then presented these results in the *Geotechnical Journal* (Estornell 1992). The GundSeal results indicated that, when the GundSeal was placed with the geomembrane backing facing downward and a defective geomembrane place on top of the bentonite portion of the GundSeal, intimate contact developed between the defective geomembrane and the bentonite. This intimate contact prevented the bentonite from becoming wet. Therefore, in situations where the GundSeal is placed with the geomembrane side down and is covered by another geomembrane, it appeared that the dry shear strength of the bentonite should be utilized for design purposes by the engineering community.

Shear strength tests were performed by Dr. Daniel and his graduate students at various normal loads on the dry bentonite (Daniel and Shan 1992). These tests were performed similarly to the tests on the hydrated bentonite and a best fit line developed by linear regression analysis was developed. The angle of internal friction reported on this best fit analysis was 22° for the dry bentonite.

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One of the characteristics noted for the failure envelopes for both the hydrated bentonite and the dry bentonite is that the failure envelopes were hyperbolic in nature. In other words, at lower normal stresses, there appears to be a higher angle of internal friction. Since in landfill cap situations, the normal stresses will be much lower than those generated on a liner system, Dr. Daniel developed failure curves for both hydrated (Daniel Nov. 1992) and the dry bentonite (Daniel June 1993) at low normal stresses. These results indicate that shear strength for the hydrated bentonite will vary from a low of 10° at normal loads of 2, 910 psf to a high of 32° at normal loads of 30 psf. The dry bentonite, when analyzed in the same way, indicates shear strength 35° at normal loads of 800 psf and less.

Some engineers have expressed concern about the bentonite becoming wet by moisture passing by diffusion through the geomembrane backing of the GundSeal geosynthetic clay liner. Dr. Daniel has performed calculations (Daniel Feb. 1992) assuming a water vapor transmission rate of .05 to .06. The data indicates that it will take approximately 1500 years for the bentonite to obtain a moisture content of 41%.

Shear strength tests were performed by Dr. Daniel and his graduate students on partially wetted bentonite samples of the GundSeal product (Daniel Feb. 1993). The results of these tests indicate that the shear strength of bentonite at the low normal stresses that will occur in a cap situation and at moisture contents in the bentonite ranging from 35 to 40% developed an angle of internal friction of 39°.

Therefore, for design purposes of landfills, the following statements can be issued. When the GundSeal product is utilized in a landfill liner with the geomembrane side facing downward and covered by an upper geomembrane, and angle of internal friction of 22° may be utilized for design purposes. In landfill cap situations where the GundSeal is utilized for design purposes. In landfill cap situations where the GundSeal is utilized with the geomembrane side facing downward and covered by another geomembrane, the angle of internal friction to be used for design purposes is 35°. In situations where the GundSeal is utilized in the cap with the bentonite side facing downward, the angle of internal friction is dependent upon a normal load acting upon the bentonite. For a cap situation where three feet of cover soils is placed on top of the GundSeal and assuming 100 pounds per cubic foot unit weight (for cover soils), a shear strength of 22° can be utilized for design purposes.

As can be seen from the data presented, there is no single shear strength for bentonite. The value to use for design purposes depends upon the moisture condition of the bentonite and the normal load acting upon the bentonite.

CETCO

COLLOID ENVIRONMENTAL TECHNOLOGIES COMPANY

MEMO

TO: Sales Managers

DATE: November 11, 1997

cc: Lori Crosson

FROM: Jim Olsta

PAGES: 9

SUBJECT: US EPA Fact Sheet - GCLs in MSW Landfills

Attached is the new fact sheet published by the US EPA Division of Solid Waste And Emergency Response. The Fact Sheet is very positive.

*The Fact Sheet states that federal municipal solid waste landfill regulations (40 CFR Part 258) allow for alternative technologies if they meet federal performance standards and that "GCL technology is an alternative that performs at or above standard federal performance levels."

*The US EPA agrees that GCLs offer advantages over conventional bottom liners and covers, including, ease of installation, low hydraulic conductivity, self-healing, and cost-effectiveness in regions where clay is not readily available.

* The US EPA states that GCLs have good internal slope stability and long-term reliability and are not affected by freeze/thaw cycles.

Unfortunately, the Fact Sheet was not circulated to the industry for comment before being issued. Consequently some of the statements are outdated.

* The US EPA indicated that there are "no standard methods for comparing GCL products". Obviously, they were not aware of ASTM Subcommittee D35.04 which has been developing standards for GCLs, six of which are currently in print.

*The Fact Sheet lists Claymax 500SP and 506SP, which are discontinued, as well as 'Bentomat DN' as 'Bentomat N'.

Overall, the Fact Sheet should be of tremendous help in gaining credibility and acceptance with the State Agencies.

United States Environmental Protection Agency

Solid Waste and Emergency Response (5306W)

EPA530-F-97-002
July 1997

EPA

Geosynthetic Clay Liners Used in Municipal Solid Waste Landfills

This fact sheet describes new and innovative technologies and products that meet the performance standards of the Criteria for Municipal Solid Waste Landfills (40 CFR Part 258).

Geosynthetic clay liners (GCLs) represent a relatively new technology (developed in 1986) currently gaining acceptance as a barrier system in municipal solid waste landfill applications. Federal and some state regulations specify design standards for bottom liners and final covers. Alternative technologies are allowed, however, if they meet federal performance standards. GCL technology is an alternative that performs at or above standard federal performance levels.

GCL technology offers some unique advantages over conventional bottom liners and covers. GCLs, for example, are fast and easy to install, have low hydraulic conductivity (i.e., low permeability), and have the ability to self-repair any rips or holes caused by the swelling properties of the bentonite from which they are made. GCLs are cost-effective in regions where clay is not readily available. A GCL liner system is not as thick as a liner system involving the use of compacted clay, enabling engineers to construct landfills that maximize capacity while protecting area ground water.

Before using a GCL in a landfill barrier system, remember there currently are no standard methods for comparing GCL products or installation systems. In addition, GCL performance properties, including the ability of GCL liner systems to effectively prevent landfill leaching, have not yet been firmly established.

This emerging technology is currently in use at a number of sites across the nation. This fact sheet provides information on this technology and presents case studies of successful applications.

GCL Technology

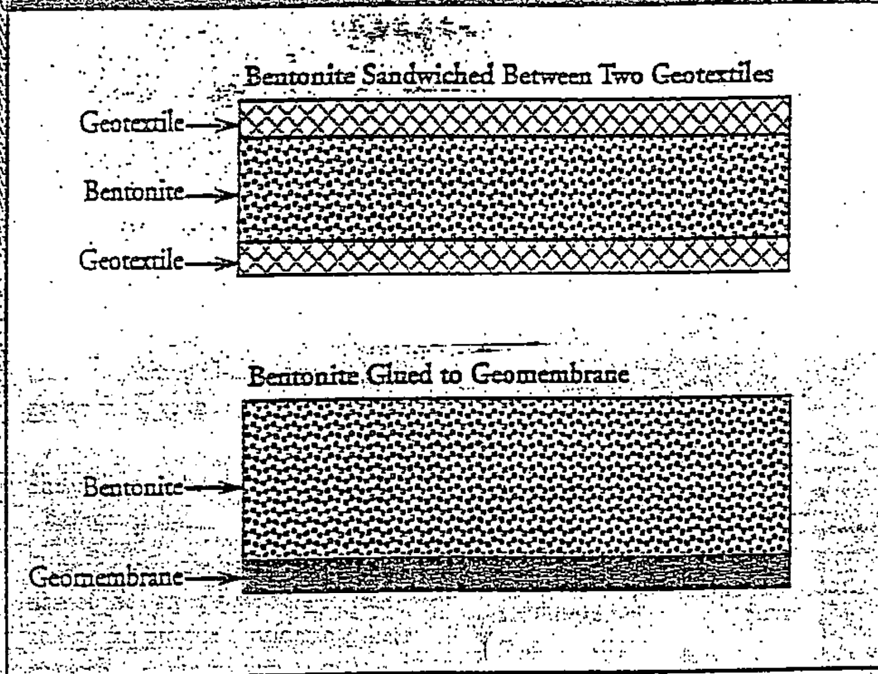
Materials

A GCL is a relatively thin layer of processed clay (typically bentonite) either bonded to a geomembrane or fixed between two sheets of geotextile. A geomembrane is a polymeric sheet material that is impervious to liquid as long as it maintains its integrity. A geotextile is a woven or nonwoven sheet material less impervious to liquid than a geomembrane, but more resistant to penetration damage. Both types of GCLs are illustrated in Figure 1. Although the overall configuration of the GCL affects its performance characteristics, the primary performance factors are clay quality, amount of clay used per unit area, and uniformity.

Bentonite is an extremely absorbent, granular clay formed from volcanic ash. Bentonite attracts positively charged water particles; thus, it rapidly hydrates when exposed to liquid, such as water or leachate. As the clay hydrates it swells, giving it the ability to "self-heal" holes in the GCL. In laboratory tests on bentonite, researchers demonstrated that a hole up to 75 millimeters in diameter will seal itself, allowing the GCL to retain the properties that make it an effective barrier system.

Printed on paper that contains at least 20 percent postconsumer fiber.

Figure 1: General Configurations of GCLs



Bentonite is affixed to synthetic materials in a number of ways to form the GCL system. In configurations using a geomembrane, the clay is affixed using an adhesive. In geotextile configurations, however, adhesives, stitchbonding, needlepunching, or a combination of the three, are used. Although stitchbonding and needlepunching create small holes in the geotextile, these holes are sealed when the installed GCL's clay layer hydrates. Figure 2 shows cross-section views of the three separate approaches to affixing bentonite to a geotextile.

Properties and Characteristics

An important criterion for selecting an effective landfill barrier system is hydraulic conductivity. Before choosing a barrier system, the landfill operator should test the technology under consideration to ensure that its hydraulic conductivity, as well as other characteristics, are appropriate for the particular landfill site.

Hydraulic Conductivity

GCL technology can provide barrier systems with low hydraulic conductivity (i.e., low permeability), which is the rate at which a liquid passes through a material. Laboratory tests demonstrate that the hydraulic conductivity of dry, unconfined bentonite is approximately 1×10^{-4} cm/sec. When saturated, however, the hydraulic conductivity of bentonite typically drops to less than 1×10^{-9} cm/sec.

The quality of the clay used affects a GCL's hydraulic characteristics. Sodium bentonite, a naturally occurring compound in a silicate clay formed from volcanic ash, gives bentonite its distinct properties. Additives are used to enhance the hydraulic properties of clay containing low amounts of sodium bentonite.

Hydraulic performance also relates to the amount of bentonite per unit area and its uniformity. The more bentonite used per unit area, the lower the system's hydraulic conductivity. Although the amount of bentonite per unit area varies with the particular GCL, manufacturers typically use 1 pound per square foot. As a result, the hydraulic conductivity of most GCL products ranges from about 1×10^{-8} cm/sec to less than 1×10^{-10} cm/sec. That is, the permeability of finished GCL products depends on a combination of factors, including the type and amount of bentonite, the amount of additives, the type of geosynthetic material, and the product configuration (i.e., the method of affixing the geosynthetic to the clay).

Shear Strength and Other Characteristics

Depending on the particular configuration of the barrier system, GCL technology can provide considerable shear strength (i.e., the maximum stress a material can withstand without losing structural integrity). In particular, a geotextile-backed GCL, with bentonite affixed via stitchbonding, provides additional internal resistance to shear in the clay layer. Needlepunching yields an even stronger, more rigid barrier. In addition, needlepunching requires the use of a nonwoven geotextile on at least one side. These GCL configurations provide enhanced interface friction resistance to the adjoining layer, an important consideration for landfill slopes.

Both needlepunching and stitchbonding, however, tend to increase the cost of the GCL product. Needlepunching, in particular, adds to a GCL's cost, because nonwoven geotextiles are generally more expensive than woven geotextiles.

Before selecting a final barrier system, landfill operators should consider other important performance characteristics, such as free and confined swelling (i.e., whether the clay will provide a uniform barrier) and rate of creep, which measures the resistance to barrier deformation.

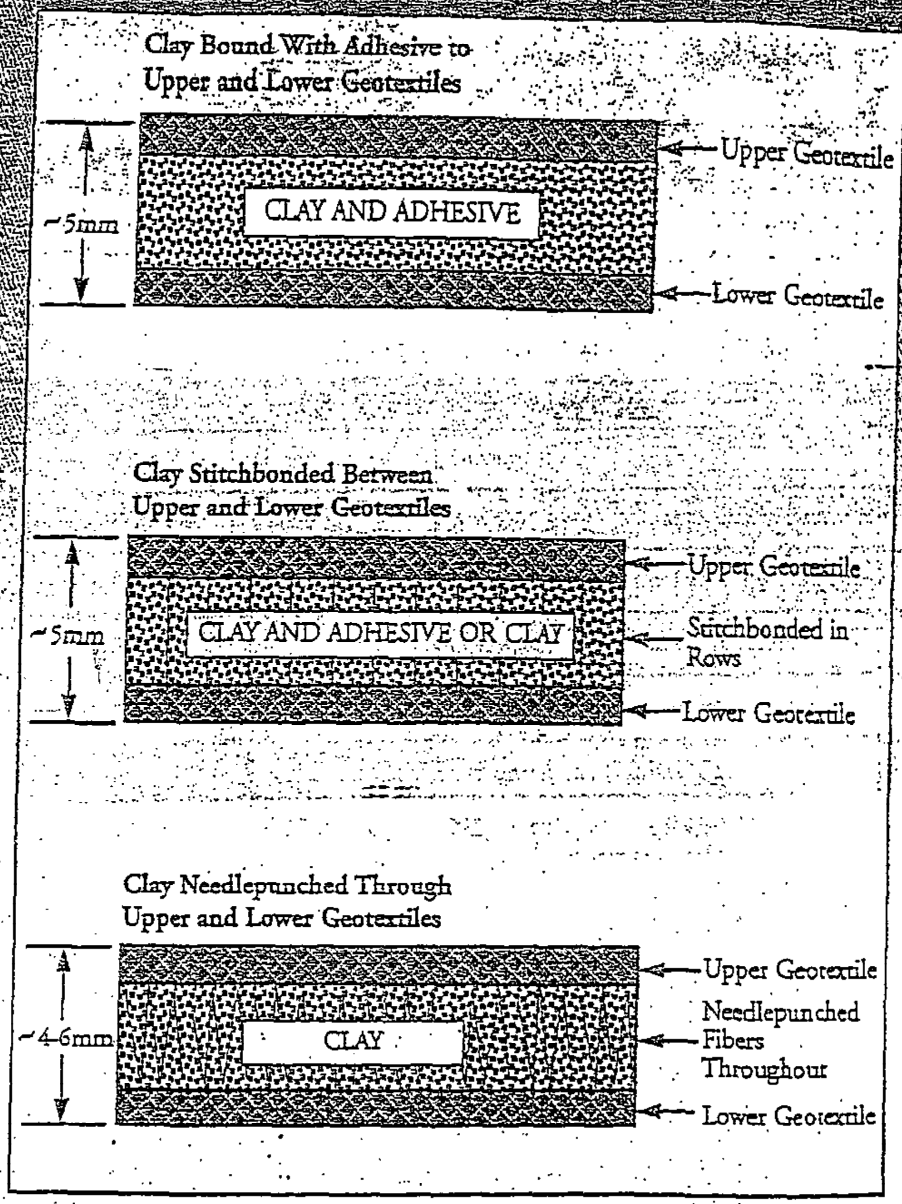
Testing

GCL configurations for barrier systems are based on the design specifications of each specific project. The American Society for Testing and Materials (ASTM) developed standardized laboratory tests for assessing mass per unit area (ASTM D 3776), hydraulic conductivity (ASTM D 5084), and direct shear (ASTM D 5321).

Researchers at the Geosynthetic Research Institute at Drexel University (in Philadelphia, Pennsylvania) and the Geotechnical Engineering Department at the University of Texas (in Austin) developed tests to measure shear strength, as well as confined swelling, rate of creep, and seam overlap permeability. These test methods have been adopted by ASTM. Additionally, the bentonite industry developed a test to measure free swell (USP-NF-XVII).

Test values for hydraulic conductivity depend on the degree of effective overburden stress around the GCL during testing. The higher the effective overburden stress, the lower the hydraulic conductivity. When comparing two different bentonite products, both must be subjected to the same degree of effective overburden stress.

Figure 2. Affixing Bentonite to Geotextiles



Available GCL Products

Product Types

The following types of GCL products are currently available:

- Geotextile type:
  - — Bentofix® (activated sodium bentonite as primary ingredient and affixed by needlepunching to a woven or nonwoven upper geotextile and a nonwoven lower geotextile).
  - — Bentomat® (sodium bentonite as primary ingredient and affixed by needlepunching to a woven or nonwoven upper geotextile and a nonwoven lower geotextile).
  - — Claymax® (sodium bentonite as primary ingredient mixed with water-soluble adhesive and bonded or stitchbonded to a woven upper and lower geotextile).
- Geomembrane type:
  - — Gundseal® (sodium bentonite as the primary ingredient mixed with an adhesive and bonded to a blend of high density polyethylene and very low density polyethylene).

Table 1 lists information on variations of these product types by manufacturer, and Figure 3 presents cross-section views of these product configurations.

In general, manufacturers ship GCL products in rolled sheets ranging from 13 to 18 feet wide and from 100 to 200 feet long. GCLs range in thickness from 0.2 to 0.3 inches.

Table 1. Principal GCL Products Available in the United States

Manufacturer & Product Name	Upper Geosynthetic[a]	Lower Geosynthetic[a]	Bonding Method	Standard Roll Width x Length (feet)
Fluid Systems, Inc. (FSI) (Germany)				
Bentofix NS	woven	nonwoven	needlepunched	(15.2 x 100)
Bentofix WP	woven	nonwoven	needlepunched	(15.2 x 100)
Bentofix NW	nonwoven[b]	nonwoven	needlepunched	(15.2 x 100)
Colloid Environmental Technologies Company (CETCO) (United States)				
Claymax 200R	woven	woven	adhered	(13.83 x 150)
Claymax 500SP	woven	woven	adhered and stitchbonded	(13.83 x 150)
Claymax 506SP	woven	woven	adhered and stitchbonded	(13.83 x 150)
Bentomat "ST"	woven	nonwoven	needlepunched	(15.3 x 125)
Bentomat "N"	nonwoven	nonwoven	needlepunched	(15.3 x 125)
GSE Environmental (United States)[c]				
Gundseal HD 20	none[d]	HDPE[e]	adhered	(17.5 x 200)
Gundseal HD 30	none[d]	HDPE	adhered	(17.5 x 200)
Gundseal HD 30	none[d]	HDPE/VLDPE[f]	adhered	(17.5 x 200)
Gundseal HD 60	none[d]	HDPE/VLDPE	adhered	(17.5 x 170)
Gundseal HD 80	none[d]	HDPE/VLDPE	adhered	(17.5 x 150)
Gundseal HD 40	none[d]	textured HDPE	adhered	(17.5 x 200)
Gundseal HD 60	none[d]	textured HDPE	adhered	(17.5 x 200)
Gundseal HD 80	none[d]	textured HDPE	adhered	(17.5 x 200)

[a] These properties vary by product and application.

[b] Nonwoven layer is scrim (a woven, open-mesh reinforcing fabric made from continuous-filament yarn) reinforced.

[c] All Gundseal products can be manufactured in 8-foot widths and with leachate-resistant bentonite. Products with backings that are 40 mils or greater can be manufactured with VLDPE as the lower geosynthetic material.

[d] Can be manufactured with a nonwoven, 0.75-ounce-per-square-yard geotextile as the upper geosynthetic material.

[e] High density polyethylene.

[f] Very low density polyethylene.

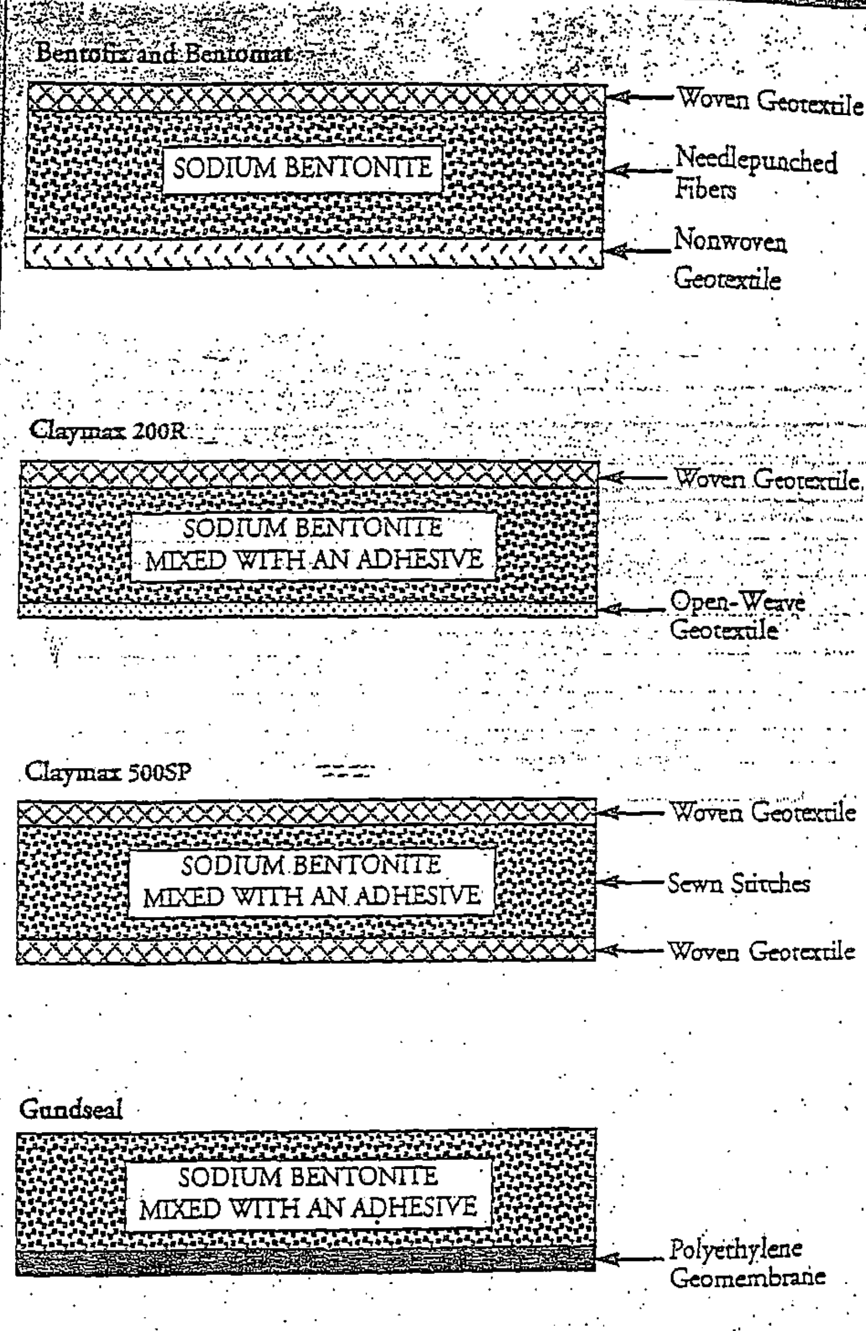
Installation

Landfill operators can install available GCL products much faster and more easily than compacted clay liners. Unlike compacted clay liners, however, GCLs are more susceptible to damage during transport and installation. Care should be taken during and after installation to avoid hydration. Hydration results in unconfined swelling of the bentonite and causes the geotextile layers to pull apart, undermining the integrity of the GCL configuration.

Manufacturers usually specify individual GCL installation procedures. Basic procedures, however, call for rolling out the large GCL sheets onto the site subgrade, which should be smooth (e.g., free of stones and grade stakes), well compacted, and dry. Once installers cover the GCL with soil, the GCL hydrates by drawing moisture from the soil. As a result, when laying out the GCL, installers must allow enough seam overlap at adjoining sheets to guard against the potential opening of the barrier system. Currently, the recommended amount of seam overlap and other seaming considerations vary with the particular GCL product. Thus, installers should follow the manufacturer's instructions for the particular product.

GCL manufacturers, and some private engineering firms, provide training for GCL installers. Among other considerations, instructions typically emphasize techniques for minimizing potential damage to the GCL during installation. The National Institute for Certification of Engineering Technologists in Alexandria, Virginia, offers a certification program in quality assurance and quality control inspection of GCL installations.

Figure 5. Available GCL Products



Costs

As of 1994, the cost of an installed GCL ranged from $0.42 to $0.60 per square foot. Factors affecting the cost of a GCL include:

- Shipping distance
- Size of the job
- Market demand
- Time of the year

In general, GCL barrier systems are especially cost-effective in areas where clay is not readily available for use as a liner material.

Issues To Be Addressed

This emerging technology requires additional field and laboratory testing to further assess its effectiveness as a landfill barrier system in terms of the key performance factors discussed below. Improved product design and installation standards must also be established.

Performance Factors

Further research is needed into the following key performance factors of GCLs.

Hydraulic Conductivity

Available data on the hydraulic conductivity of various GCL configurations are gathered exclusively under laboratory conditions. Data from field tests should be collected to establish product design values.

Bearing Capacity

A study by the Geosynthetic Research Institute provides the basis for allaying some concerns about the bearing capacity of hydrated GCLs, but more research is needed. The study demonstrated that an adequate layer of cover soil (according to the product manufacturers' recommendations), placed on GCLs during installation, prevents a decrease in liner thickness with the application of a load. Without a sufficient soil layer, GCLs become compressed, raising their hydraulic conductivity (i.e., making them more permeable) and reducing their effectiveness as a barrier.

Slope Stability

Research is ongoing on the slope stability of GCLs used in landfill sidewall applications to determine whether this use of GCLs provides sufficient resistance to internal shear and physical displacement. Additional data are needed to support the preliminary results of a U.S. Environmental Protection Agency field study indicating good stability of GCL technology following capping operations. This study mimicked the construction stresses all four GCL products (see Figure 3) are subjected to during capping. Constructed in November 1994, the study site used five plots of GCL placed at a 3 to 1 slope and eight plots placed at a 2 to 1 slope. All plots had a 3-foot-thick soil cap. Researchers collected information on the soil and clay moisture of the GCL using internal probes, and they measured the GCL for physical displacement. Results to date indicate good slope stability for all plots.

Long-Term Reliability

The geotextile or geomembrane in GCL products remains durable for long periods of time.

Freeze and Thaw Cycles

Freeze and thaw cycles do not affect GCLs used in landfill bottom liner applications because these systems are installed below the frost line. Limited laboratory data indicate that the hydraulic conductivity of GCLs is not affected by freeze and thaw cycles. Laboratory tests performed on a bentonitic blanket indicate that hydraulic conductivity before freezing of 2×10^{-11} cm/sec was unaltered after five freeze and thaw cycles. Full-scale field tests still must be conducted, however, to corroborate the laboratory data, especially for GCL technology used as an infiltration barrier in landfill caps.

Design and Installation Standards

The following issues must be addressed to encourage the further development of GCL technology as a landfill barrier system.

Material Properties and Additional Testing Methods

To allow design engineers to develop more precise site specifications, a list of important performance properties for materials used in GCL products, as well as minimum performance values, must be established. Additional testing procedures must be developed, and all methods should be standardized to facilitate the realistic comparison of different GCL products.

Construction and Installation Procedures

Standardized practices must be developed to address GCLs' vulnerability to the following:

- System stress from inclement weather after installation.
- Potential for lack of hydration of bentonite clay in arid regions.
- Punctures in the barrier system (reducing the barrier potential of both the clay and the geosynthetics).
- System decay caused by biological intruders, such as burrowing animals and tree roots (potentially affecting both the clay and the geosynthetics).

Additionally, a standardized quality assurance and quality control program must be developed.

Case Studies

The following case studies illustrate some of the uses of GCL technology as a barrier system in landfills. Currently available information from these sites relates to installation only; long-term performance is still being assessed. Only one of the studies concerns the use of GCL technology in bottom liner applications, because this use is relatively new. The other two studies focus on cap system applications, which represent a slightly more established use of the technology. The case studies represent sites in three different geographic regions and involve three different GCL products.

GCL Landfill Liner: Broad Acre Landfill Pueblo, Colorado

Broad Acre Landfill installed a liner system in 1991 that included:

- A 60-mil Gundseal GCL
- 1 foot of compacted clay

According to landfill operators, the Gundseal was easy to work with. They installed 200,000 square feet in 1 week. Workers installed the liner with the bentonite side down (i.e., the geomembrane side up). As of February 1996, landfill officials reported that the liner was functioning effectively. No releases of leachate have been detected by the ground-water monitoring system.

GCL Landfill Cap: Whyco Chromium Landfill Thomaston, Connecticut

During July 1989, Whyco Chromium Landfill installed a Claymax 200R GCL in a cap system that included the following (from top to bottom):

- 6 inches of topsoil
- 24 inches of earthen material
- Geogrid (for tensile strength)
- Geotextile
- Polyvinyl chloride geomembrane (30-mil thickness)
- Claymax
- Geotextile

The landfill site occupies 41,000 square feet, and workers installed the Claymax product in 1 day. Thus far, the cap is functioning well.

GCL Landfill Cap: Enoree Landfill Greenville, South Carolina

In August 1994, the first phase of closure at the Enoree Landfill involved installing the following cap system:

- 6 to 12 inches of new and native soil
- 18 inches of compacted clay
- Bentofix GCL

Enoree staff capped approximately 26 acres of the landfill in 6 weeks. Landfill officials report that the cap is functioning effectively.

The mention of publications, products, or organizations in this fact sheet does not constitute or imply endorsement or approval for use by the U.S. Environmental Protection Agency.

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TECHNICAL EQUIVALENCY ASSESSMENT OF GCLs TO CCLs

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ABSTRACT

Since their introduction as barrier materials in waste containment systems in 1986, geosynthetic clay liners (GCLs) have been installed in a variety of applications. Perhaps the major applications have been as leachate containment barriers beneath landfills and surface impoundments, and as infiltration water barriers in landfill covers. When one considers that the traditional barrier material in these applications is a compacted clay liner (CCL), it is only logical that the two materials should be compared and contrasted to one another in such a way so as to assess technical equivalency. This paper provides the salient features for providing such an assessment. It is primarily based on technical issues and results in a framework that can possibly be used for assessment of both liner and cover barrier materials.

In this assessment it is seen that other than issues of puncture resistance and product thinning due to abutting objects and uneven subgrades (both of which can be avoided by proper CQC/CQA procedures), GCLs can generally be used on an equivalent basis as CCLs. However, site specific conditions like long term slope stability may provide unique situations calling for specific products or alternate designs.

Needed to further this assessment of GCLs to CCLs is a continued dialogue with respect to technical issues, close monitoring of GCL installations, and involvement of regulatory agencies in the decision making process.

INTRODUCTION AND SCOPE

The traditional hydraulic barrier material used to contain solids and liquids in a variety of applications is clearly one made from natural soils, typically clays. Such clay barriers can occur via a natural clay stratum, a compacted soil liner or an amended clay liner. These natural soil materials will be called by the collective term of "compacted clay liners", or "CCLs", in this paper.

Clearly, CCLs are the basic material required by regulatory agencies in the containment of solid waste. A recent study for municipal solid waste liner systems has shown the following, Fahim and Koerner (1993):

- CCLs are used as a single liner beneath waste in 19 states
- CCLs are used as a composite liner beneath a geomembrane in 20 states
- CCLs are used as a single cover in 36 states
- CCLs are used as a composite cover beneath a geomembrane in 6 states

The minimum U. S. EPA requirements are generally for the CCL to be from 300 to 900 mm thick with a maximum hydraulic conductivity of 1×10^{-7} cm/sec in the liner and 1×10^{-5} cm/sec in the cover. Note, however, that current municipal solid waste regulations (Subtitle "D") call for a geomembrane to be placed above the CCL in both situations of a liner beneath the waste and a cover above the waste.

A tremendous data base is available on CCLs for waste containment applications. This is evidenced by major research efforts, U.S. EPA SW-869 (1983), Goldman, et. al. (1988) and Daniel, (1987), development of specialized laboratory test equipment, U.S. EPA (1986), development of unique construction procedures and equipment, Rogowski, (1990) and an entire CQC/CQA monitoring protocol, Daniel and Koerner (1993). Thus any new liner material intended to challenge the status of CCLs must necessarily be compared and contrasted to the existing situation.

One such competing material that might be considered for a single liner (not a composite) replacement of a CCL is a geomembrane (GM). Indeed, 8 states have selected this option for liners beneath the waste and 17 have for covers above the waste. Both strategies, however, do not meet the minimum technology guidance of U.S. EPA regulations which, as mentioned previously, require composite GM/CCL systems. For this paper it will be assumed that the GM (if used at all) will be used in a complimentary manner to the underlying clay liner as a composite liner.

A second, and more recent, competing material to a CCL is a geosynthetic clay liner, or GCL. Geosynthetic clay liners are defined in ASTM D4439 as follows:

"Geosynthetic clay liners are factory manufactured hydraulic barriers typically consisting of bentonite clay or other very lower permeability material, supported by geotextiles and/or geomembranes, which are held together by needling, stitching, or chemical adhesives."

Bentonite panels (the forerunner to GCLs) were first manufactured in the early 1980's and were initially used for foundation waterproofing and for sealing water retention structures. The panels were subsequently modified to be flexible rolls incorporating either geotextiles or geomembranes, i.e., GCLs, and were first used for landfill liners in 1986. Since then, GCLs have been used for a variety of lining applications and final cover systems for municipal and hazardous solid wastes.

The realization that GCLs are new, however, is evidenced by the survey mentioned earlier, Fahim and Koerner (1993), where no Federal regulations and only two State regulations even mention GCLs as a possible replacement of, or augmentation to, CCLs. In Colorado, GCLs are possible to use in the liner system and in Michigan in the cover system.

Interestingly, replacement of any natural material with a synthetic alternative (via technical equivalency) is usually a possibility. If one wishes to substitute a GCL for a CCL, one must demonstrate that the GCL will be equivalent in terms of meeting performance objectives. However, neither Federal nor State regulations mention the criteria by which equivalency should be evaluated. At the present time equivalency must be evaluated on a case-by-case basis using criteria that have not yet been defined. The lack of equivalency accepted criteria is perhaps the single greatest problem that the designer and/or owner of a waste facility face in seeking regulatory approval for substitution of a CCL by a GCL.

Importantly, one should not think of a GCL as being totally equivalent to a CCL. Indeed, there is no possibility that a 10 mm thick layer of bentonite could possibly be equivalent to a 300 to 900 mm thick layer of compacted clay in all respects. The critical issue is whether substituting an alternative material such as a GCL for the more traditional CCL will meet or exceed the performance objectives of the site specific situation. If the GCL will meet or exceed the performance objectives, then it should be considered that equivalency has been established.

This paper is intended to establish a framework for assessing such equivalency for waste containment liners and covers. In so doing, many generalities must be taken since no two site performance objectives, or set of demands, are identical. Even further (and with respect to solid waste landfills), liner systems beneath the waste will have very different objectives than covers above the waste. With these concepts in mind, and for the purposes of this paper, GCLs will be contrasted to CCLs in both liners and covers from a generic and widely encompassing perspective.

OVERVIEW OF GCLs

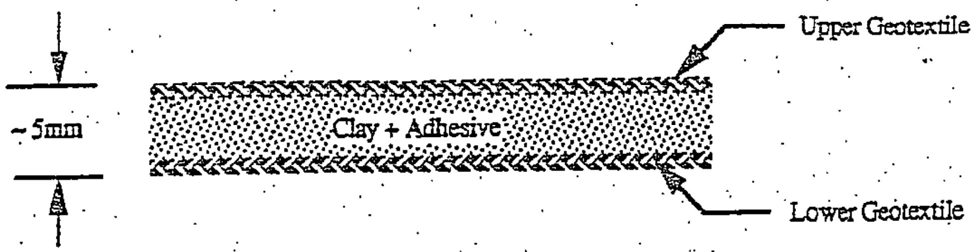
Since compacted clay liners (CCLs) are historically known, clearly established and well documented, e.g., U.S. EPA SW-869 (1983), Goldman, et. al. (1988), and Daniel, (1987), we will only focus on a description of geosynthetic clay liners (GCLs). The description will be brief, however, since more complete descriptions are available in the open literature, Daniel and Boardman (1993) and Estornell and Daniel (1992), and can be regularly updated from manufacturers of the various GCL products.

The essence of a GCL, of course, is the layer of bentonite which is held between or on carrier layers of geotextiles or a geomembrane. Bentonite is a unique clay mineral with very high swelling potential and water absorption capacity. When wetted, bentonite is the least permeable of all naturally occurring, soil-like minerals. Bentonite is a chemically stable mineral that has undergone complete weathering and will last, in effect, forever.

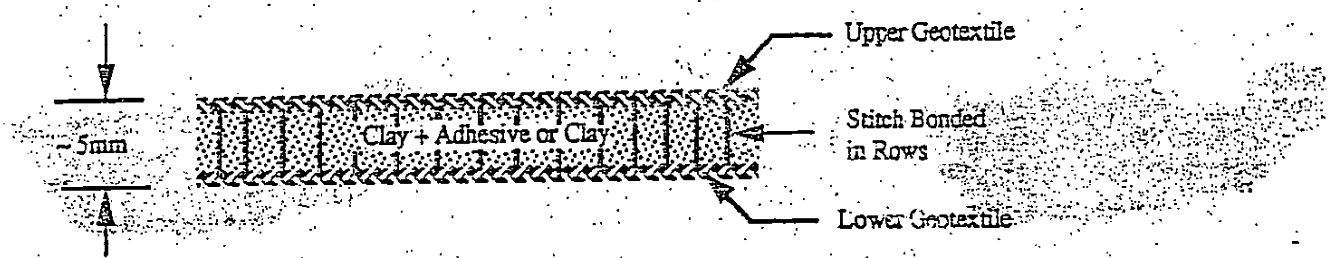
GCLs are manufactured by placing powdered or granulated bentonite (with or without an adhesive mixed into the bentonite) on a geotextile or geomembrane substrate. The bentonite layer is typically 7 to 10 mm thick and is placed at a unit weight of approximately 5.0 kg/m^2. Those GCLs with a geotextile substrate (4 of the 5 available types) have covering geotextiles as well, see Figure 1(a). The product (with or without adhesives) is often stitch bonded as in Figure 1(b), or needle punched as in Figure 1(c), thereby gaining considerable structural integrity. For one GCL, the substrate is a geomembrane where an adhesive mixed with the bentonite results in the final product, see Figure 1(d).

One particular style of each of the commercially available GCL products is shown in the upper photograph of Figure 2. This photograph shows the products stacked upon each other in dry (lower) and hydrated (upper) pairs. The lower photograph shows greater detail of one of the products in the hydrated (left) and dry (right) states.

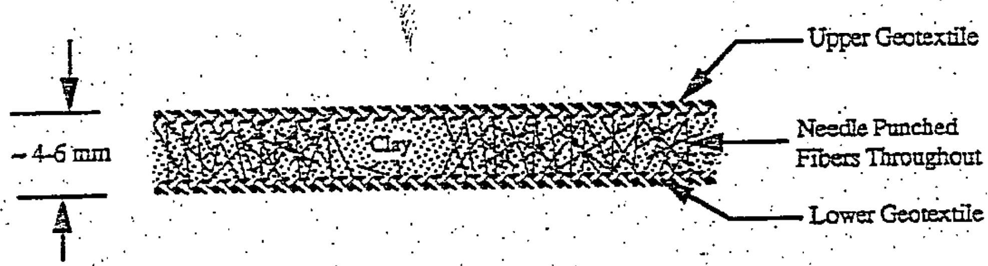
As one can surmise from these photographs, there exists very real differences between GCLs and a 300 to 900 mm thick layer of clay soil. In addition to the obvious thickness issue, Table 1 counterpoints many of the relevant features. Daniel (1993) further elaborates on these differing features.



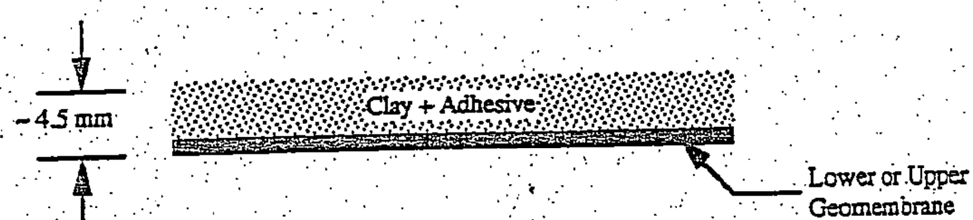
(a) Adhesive Bound Clay to Upper and Lower Geotextiles



(b) Stitch Bonded Clay Between Upper and Lower Geotextiles

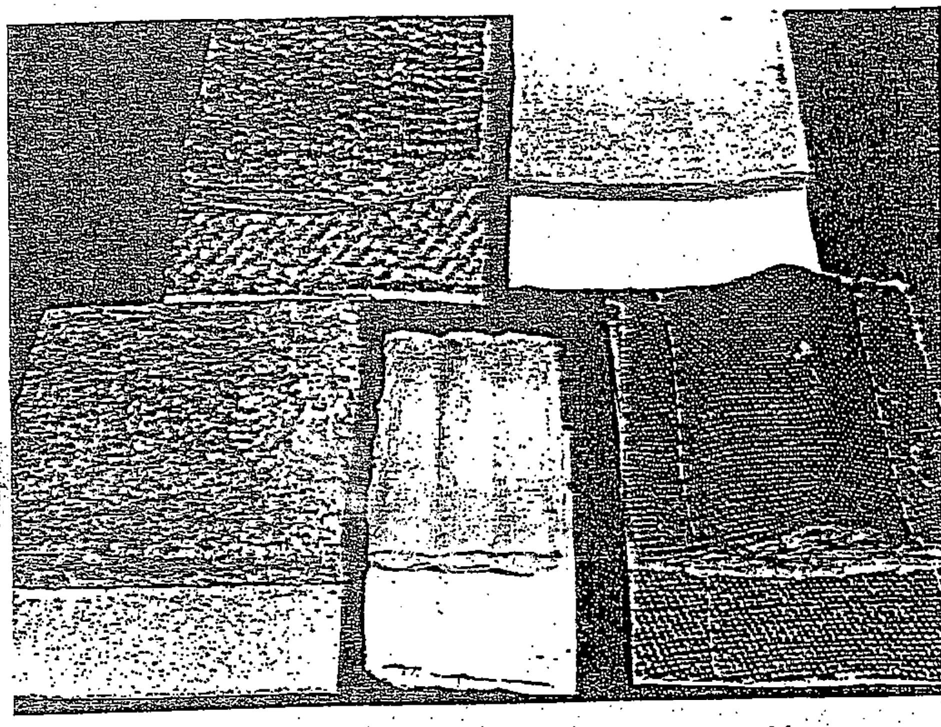


(c) Needle Punched Clay Through Upper and Lower Geotextiles

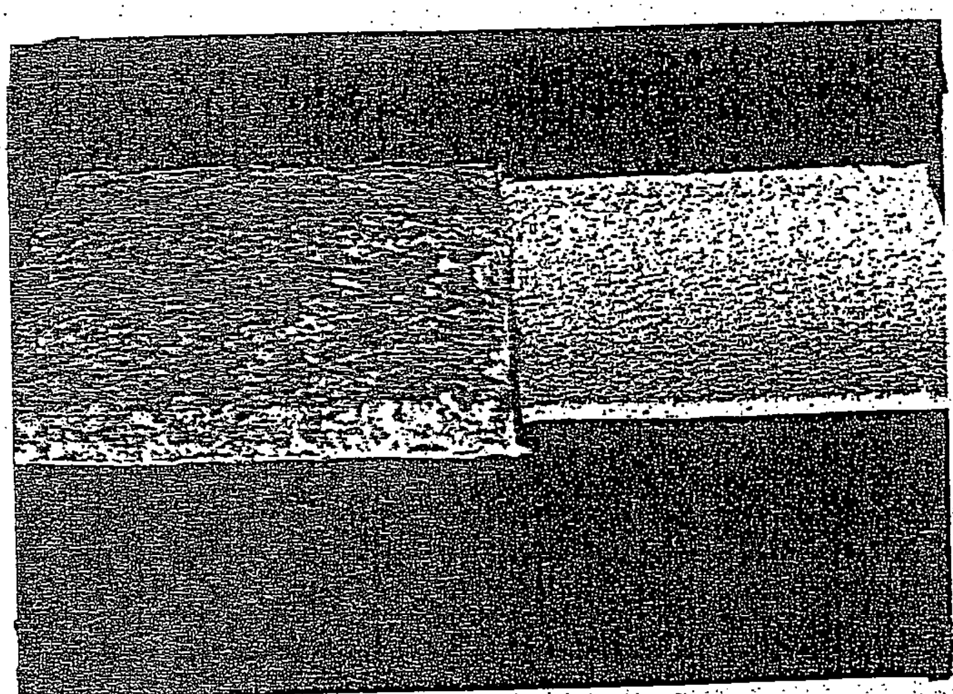


(d) Adhesive Bound Clay to a Geomembrane

Figure 1. Cross section sketches of currently available geosynthetic clay liners (GCLs).



(a) Different Products in Dry versus Hydrated Conditions



(b) A GCL Hydrated (Left) vs. Dry (Right)

Figure 2. Commercially Available Geosynthetic Clay Liners (GCLs)

Table 1. Some selected differences between GCLs and CCLs.

Characteristic	Geosynthetic clay liner	Compacted clay liner
Materials	Bentonite, adhesives, geotextiles, and geomembranes	Native soils or blends of native soils and bentonite
Thickness	Typically 7 to 10 mm (when hydrated)	Typically 300 to 900 mm
Hydraulic conductivity	$\leq (1 \text{ to } 5) \times 10^{-9}$ cm/s	$\leq 1 \times 10^{-7}$ cm/s
Speed of construction	Rapid, simple installation	Slow, complicated construction
Need for MQC and MQA	Factory manufacturing requires constant monitoring	Naturally found materials or mineral layers requiring no monitoring
Status of CQC and CQA	Relatively simple, straight-forward, common-sense procedures	Complex procedures requiring highly skilled and knowledgeable people
Field desiccation sensitivity	GCLs cannot desiccate during construction unless prematurely hydrated	CCLs are nearly saturated; can desiccate during construction
Available of materials	Materials readily shipped to any site	Varies widely from readily available to not available at all
Installed Cost	Typically \$6.00 to \$8.00 per square meter for a large site	Highly variable – estimated range: \$6.00 to \$30.00 per square meter
Experience	Limited due to newness and nonfamiliarity	Has been used for many decades with great confidence as a liner material

Note:
MQC = manufacturing quality control
MQA = manufacturing quality assurance
CQC = construction quality control
CQA = construction quality assurance

TECHNICAL EQUIVALENCY ISSUES

In this section as many issues as felt to be typically encountered in comparing GCLs to CCLs are presented. They are arranged in three somewhat arbitrary categories (hydraulic, physical/mechanical and construction) and are listed for liners as well as covers. Each of the issues in Table 2 will be discussed individually in the text to follow.

Table 2. Technical equivalency categories and specific issues to be addressed.

Category	Criterion for evaluation	Possibly relevant for: Liners	Covers
Hydraulic Issues	Steady flux of water	X	X
	Steady solute flux	X	
	Chemical adsorption capacity	X	
	Breakout time:		
	- Water	X	X
	- Solute	X	
	Horiz. flow in seams or lifts	X	X
	Horiz. flow beneath geomembranes	X	X
	Generation of consolidation water	X	X
	Permeability to gases		X
Physical/ Mechanical Issues	Freeze-thaw behavior	X[1]	X
	Wet-dry behavior		X
	Total settlement response	X[2]	X
	Differential settlement response	X[2]	X
	Slope stability considerations	X	X
	Vulnerability to erosion		X
	Bearing capacity (squeezing)	X	X
Construction Issues	Puncture resistance and resealing	X	X
	Subgrade condition considerations	X	X
	Ease of placement or construction	X	X
	Speed of construction	X	X
	Availability of materials	X	X
	Requirements for water	X	X
	Air pollution concerns	X	X
	Weather constraints	X	X
	Quality assurance considerations	X	X

notes:
[1]Relevant only until liner is covered sufficiently to prevent freezing
[2]Settlement of liners usually of concern only in certain circumstances, e.g., vertical or lateral expansions

HYDRAULIC ISSUES

The essence of any barrier material is its ability to contain the targeted liquids. The usual liquids are leachate, i.e., the solute, for liner systems beneath the waste and water for the cover system above the waste.

Steady Flux of Water. Water flux is defined as the volume of water flowing across a unit area in a unit time. The steady downward flux of water (v) through an individual layer of porous material with zero water pressure at the base of the layer is defined from Darcy's law as:

$$v = k\,\frac{H+T}{T} \qquad (1)$$

where k is the hydraulic conductivity, H is the depth of liquid ponded on the layer, and T is the thickness of the layer.

Equation 1 is applicable only for flow through the bentonite component of a GCL; if the GCL contains a geomembrane, water flux will be controlled by water vapor diffusion through the geomembrane component. The geomembrane component, if present, should be included in the equivalency analysis, e.g., by using appropriate water vapor transmission rates. Also, Eq. 1 applies to a CCL or GCL liner alone and not to composite liners. Composite action with a geomembrane is considered later.

In order to estimate the required hydraulic conductivity of the GCL for equivalency assessment, assume that the water flux through the GCL is equal to the water flux through the CCL:

$$v_{GCL} = v_{CCL} \tag{2}$$

or:

$$k_{GCL}\frac{H+T_{GCL}}{T_{GCL}} = k_{CCL}\frac{H+T_{CCL}}{T_{CCL}} \tag{3}$$

If the hydraulic conductivity and thickness of the compacted clay liner are known, and the thickness of the GCL is known, the required hydraulic conductivity of the GCL to ensure equivalent performance in terms of steady flux of water is:

$$(k_{GCL})_{Required} = k_{CCL}\frac{T_{GCL}}{T_{CCL}}\frac{H+T_{CCL}}{H+T_{GCL}} \tag{4}$$

The required hydraulic conductivity of the compacted clay liner (k_{CCL}) is usually 1×10^{-7} cm/s. The thickness of GCLs (T_{GCL}) varies from product to product, but is typically about 7 mm after hydration at low overburden stress. The head of water (H) on the CCL or GCL is assumed to be 300 mm for purposes of illustration. The required hydraulic conductivity of the GCL, based on Eq. 4 and these conditions, is therefore:

- For equivalence to a 300-mm-thick compacted clay liner:
  $(k_{GCL})_{Required} = 4.6 \times 10^{-9}$ cm/sec
- For equivalence to a 600-mm-thick compacted clay liner:
  $(k_{GCL})_{Required} = 3.4 \times 10^{-9}$ cm/sec

As see in Table 1, the hydraulic conductivity of the bentonite component of commercially-produced GCLs is typically ≤ 1 to 5×10^{-9} cm/s. Thus, it is seen that equivalency of a GCL to a CCL, in terms of the steady water flux, can be established for most, if not all, GCLs in their manufactured condition.

<u>Steady Solute Flux</u>. Long-term, steady flux of solute in leachate may be analyzed on the basis of advection alone, diffusion alone, or advection plus diffusion. It is assumed that the concentration of a solute of concern in the leachate remains constant. Regarding advection, the advective mass flux, $v_{m,A}$, is:

$$v_{m,A} = c_{leachate}\, k\frac{H+T}{T} = c_{leachate}\, v \tag{5}$$

where $c_{leachate}$ is the concentration of the solute of interest in the leachate and, as before, v is the water flux. The advective mass flux ratio, $F_{m,A}$, is defined as the mass flux of solute through a GCL divided by the mass flux of solute through a CCL:

$$F_{m,A} = \frac{v_{m,A(GCL)}}{v_{m,A(CCL)}} \tag{6}$$

or:

$$F_{m,A} = \frac{c_{leachate}\, k_{GCL} \dfrac{H + T_{GCL}}{T_{GCL}}}{c_{leachate}\, k_{CCL} \dfrac{H + T_{CCL}}{T_{CCL}}} = \frac{c_{leachate}\, v_{GCL}}{c_{leachate}\, v_{CCL}} = \frac{v_{GCL}}{v_{CCL}} \tag{7}$$

Thus, the ratio of solute flux is the same as the ratio of water flux. Therefore, if one has demonstrated equivalency in terms of steady water flux, one has necessarily also demonstrated equivalency in terms of steady mass flux of solute.

Chemicals can also migrate through liners via diffusion. Two cases are considered:

1. Single Liner or Bottom Liner in Double Liner System. Theoretically, steady-state diffusion is never reached with a clay liner resting on native soil, unless there is a boundary condition, e.g., water table with uncontaminated water at a shallow depth below the liner. Conditions at a particular site must be considered in order to determine the pattern of diffusion through a liner resting on native soil. However, in nearly all cases essentially equivalent performance is anticipated from a GCL if the native soils are included in the assessment, as they should be.

2. Upper Liner in Double Liner System. Over time, the solute of interest in the leachate will diffuse to the base of the upper liner and into ~~the~~ underlying leak detection layer. The concentration at the base of the liner will eventually equal the concentration on top of the liner. Thus, the diffusion-driving concentration gradient will become zero and diffusive transport will cease. The issue of steady diffusion through an upper liner in a double liner system is moot.

Solutes can also migrate through soil liners by advection plus diffusion. However, since advective and diffusive mass fluxes are additive, and since the advective mass flux dominates, demonstration of equivalency in terms of water flux will generally ensure equivalency in terms of total mass flux.

Chemical Adsorption Capacity. Regulations generally have no specific adsorption requirements. Adsorption of organics tends to be different from adsorption of inorganics. Adsorption of inorganics is controlled by cation exchange reactions and geochemical processes such as precipitation. Adsorption of organic solutes is generally assumed to be controlled by the amount of organic carbon in the soil and a partition coefficient for the solute (which is characterized by the octanol-water partition coefficient or water solubility of the organic species).

For inorganics, the maximum adsorbed mass per unit cross-sectional area of liner (M) resulting from cation exchange processes may be defined as follows:

$$M = C\rho_d T \tag{8}$$

where C is the cation adsorption capacity (maximum mass of solute sorbed per unit mass of dry soil), ρ_d is the dry mass density of the soil, and T is the thickness of the liner. The ratio of thickness of a typical GCL to a CCL is small (on the order of 0.01). Thus, in order for a GCL to have equivalent cation adsorption capacity, the adsorption coefficient of the GCL would have to be at least 100 times that of the CCL.

The cation exchange capacity of bentonite clay is typically on the order of 100 to 150 meq/100g. Natural soil materials used to construct CCLs have typical CECs in the range of 3 to 30 meq/100g. The ratio of cation adsorption capacities, denoted F_{CEC}, is:

$$F_{CEC} = \frac{C_{GCL}}{C_{CCL}} = \frac{C_{GCL}}{C_{CCL}\frac{\rho_{dGCL}}{\rho_{dCCL}}}\frac{T_{GCL}}{T_{CCL}} \qquad (9)$$

For the typical range of values, F_{CEC} would be expected to be in the range of 0.03 to 0.75. It appears unlikely that equivalency can be demonstrated for cation adsorption capacity using the expressions just presented. However, cation exchange is just one of several processes that can affect adsorption. Precipitation of inorganic solutes can be a far more important mechanism than cation exchange, and pH is often a dominant variable controlling precipitation processes in many geochemical environments. Thus, site-specific factors, and not just simple comparisons of CECs and relative soil masses, will often need to be considered when relative adsorption capacities are compared.

Non-polar organic solutes are sorbed by carbon present in the soil. The carbon content of bentonite in GCLs is capable of estimation, but CCLs will be highly variable in their organic carbon content. Although site-specific assessments would be required (due to variability of CCLs), equivalency of a GCL to a CCL probably cannot be demonstrated in terms of capacity to adsorb non-polar constituents in leachate because the mass of bentonite present in a GCL is far less than the mass of soil present in a CCL.

Adsorption, however, is only relevant in the short-term. When steady state mass transport is reached, adsorption capacity is exhausted. Equivalency in terms of adsorption, if evaluated at all, should be evaluated in terms of a specified performance period.

<u>Breakout Time of Water or Solute</u>. Neither GCLs, nor CCLs, are initially saturated with water. GCLs contain essentially dry bentonite, but CCLs are often close to being saturated at the time of construction. When liquid first enters the upper surface of an unsaturated liner, no liquid discharges from the base of the liner until the liner absorbs enough water to reach field capacity at the base of the liner.

The time to discharge water from the base of the liner is difficult to analyze in a simple way. For CCLs, the time depends greatly upon the hydraulic conductivity, initial water content, tendency to swell, and rate of water infiltration into the top of the liner. For GCLs, the time to initiate discharge of water from the base is usually fairly short (a few weeks) if the liner is continuously flooded with solute or may be extremely long if solute is slowly absorbed by the bentonite. For GCLs that contain a geomembrane, the time may be much greater. A comparison of time to initiate discharge of solute from the base of the liner would have to be performed on a site and product specific basis.

Regarding a landfill cover, a GCL might be compared to a CCL in terms of the time to discharge water from its base on the assumption that leachate production within the underlying waste would not begin until water is discharged from the base of the barrier layer. However, many would consider the "breakout time" of water from the barrier layer to be essentially irrelevant because over the long term, the time to initiate discharge water from the barrier layer is not important. Over the long term, the flux of water through the barrier layer is the important issue. A liner with a hydraulic conductivity of 1×10^{-9} cm/s allows only about 0.25 mm (0.01 inch) of water to flow through it per year under continuous exposure to a water source and unit hydraulic gradient. For those GCLs that contain a geomembrane, the presence of the geomembrane should be taken into account in the evaluation of breakout time.

In general, it is not believed that breakout time should be an important issue in an equivalency assessment. Other factors seem far more important.

Horizontal Flow in Seams or Lifts. The liquid flow just described is considered to be, and is laboratory measured as, the vertical flow through the clay matrix. Concerns are raised as to horizontal flow which might be more rapid and tend to increase the water or solute flux over a large area. For GCLs, the concern is clearly in the overlap seam area. Yet, large scale experiments tend to substantiate manufacturers recommendations that the overlap areas either self-seal or, by adding bentonite, co-mingle with the abutting geotextiles to form an adequate seal, LaGatta, (1992). For CCLs, the concern is between individual lifts with inadequate bonding from one surface to the next, Rogowski (1990). This issue, as with the GCLs, is clearly related to CQC/CQA monitoring which will be discussed later. If properly constructed, neither material should be a major concern with respect to horizontal liquid flow.

Horizontal Flow Beneath Geomembranes. When used as the lower component of a composite liner, both GCLs and CCLs must achieve "intimate contact" with the overlying geomembrane. The reason being that liquid (water or solute) passing through a hole in the geomembrane should not be able to spread horizontally attacking the underlying clay over an enlarged area.

Using a radial transmissivity device, laboratory test results on five different GCLs placed beneath a geomembrane with a small centrally located hole has been reported by Harpur, et al. (1993). Transmissivity test results at two different normal stresses were evaluated, see Table 3.

Table 3. Apparent transmissivities of various GM/GCL combinations compared to theoretical GM/CCLs.

Clay Beneath Geomembrane	Type of Bentonite	Type of Upper Geotextile Against Geomembrane	Apparent Transmissivity in Units of m^2/sec	
			7 kPa	70 kPa
GCL-A	adhesive/granules	none	3×10^{-12}	3×10^{-12}
GCL-B	power	woven-slit film	3×10^{-11}	9×10^{-12}
GCL-C	adhesive/granules	woven-spunlaced	8×10^{-11}	6×10^{-12}
GCL-D	granules	woven-slit film	2×10^{-10}	1×10^{-10}
GCL-E	powder	nonwoven-needled	1×10^{-10}	8×10^{-11}
theoretical best CCL lab conditions		none	6.4×10^{-10}	
theoretical best CCL field conditions		none	6.4×10^{-9}	

Comparing the GCL group with CCLs is difficult due to lack of data with GM/CCLs. However, theoretical data also shown in Table 3 indicates that all GM/GCL combinations evaluated are significantly lower in transmissivity than the anticipated GM/CCL transmissivity. Bentonite extruding through covering geotextiles, or intruding into them gives rise to these lower GM/GCL transmissivity values. While actual GM/CCL data needs to be developed it appears as though GCLs are superior to CCLs with respect to transmissivity.

For both GCLs and CCLs, the intimate contact issue can be challenged when the covering geomembrane has waves in it due to high temperature expansion. This is an equal concern for both GCLs and CCLs with no preference for one material over the other.

Generation of Consolidation Water. Application of normal stress to a CCL tends to squeeze water out of the clay matrix. If this were to occur in a landfill cover, the water migrating into the underlying waste would eventually become leachate. Dry GCLs have no capability to produce consolidation water upon loading. In general, the GCL should be viewed as superior to a CCL in terms of minimizing production of consolidation water. However, because the applied loads in final covers are so small, the entire issue of production of consolidation water is usually moot for covers. This issue is far more important for clay liners located above leak detection layers in double liner systems beneath landfills.

In double lined waste containment facilities at least six states require a composite primary liner located above a leak detection system for MSW, Fahim and Koerner (1993). For hazardous waste, the number is considerably higher. When the clay liner component is a CCL placed at, or near, saturation, each lift of solid waste placed in the facility causes consolidation to occur. The expelled water enters the leak detection system and invariably causes confusion. Is the liquid consolidation water or leachate passing through the entire primary composite liner? Only through chemical analysis (MS/GC testing) and comparison with the primary leachate can a definitive answer be given. Additionally, this generation of expelled pore water occurs with each lift of additional waste that is placed in the facility. It has been very troublesome (and difficult to interpret) at a number of facilities. Dry GCLs do not have this problem and can be considered superior in this regard.

Permeability to Gases. The permeability of a barrier layer to various gases may be very important if the barrier layer is expected to restrict the movement of gas through the cover of a MSW landfill. Decomposing MSW landfills produce methane, carbon dioxide and trace amounts of numerous other gases. For clay soils, the gas permeability is extremely sensitive to the water content of the soil. Dry clay materials are highly permeable to gases, but water-saturated clay materials are practically impermeable to gases.

Compacted clay liners are compacted at a water content that is wet of optimum. The volume of air present in the CCL tends to be very low. Conversely, the gas permeability of GCLs depends greatly on how much moisture has been absorbed by the bentonite. The gas permeability is high for dry bentonite sandwiched between two geotextiles. For GCLs that contain a geomembrane, the geomembrane dominates the material's gas permeability and gives it a very low permeability. Equivalency in terms of gas permeability probably can be demonstrated for GCLs that contain a geomembrane or for GCLs that are sufficiently hydrated to attain a low permeability to gages. The bentonite in the GCL can be forced to hydrate quickly either by placing the GCL in contact with a moist soil or by applying water to the overlying soil after the GCL is placed and covered. Laboratory tests indicate that absorption of water by the bentonite occurs within a few weeks, Daniel, et al. (1993). The hydration of the bentonite can be forced to occur if gas permeability is a critical issue.

While this discussion tends to favor CCLs, it must be mentioned that if the CCL cracks due to desiccation or differential settlement the preferred pathways will bypass the intact soil mass causing the CCL to become high in its gas permeability.

PHYSICAL/MECHANICAL ISSUES

A number of physical/mechanical issues must be addressed since an inadequate structural performance of either a CCL or a GCL could result in an inadequate hydraulic performance, or even result in a failed system.

Freeze/Thaw Behavior. CCLs are known to be vulnerable to large increases in hydraulic conductivity from freeze/thaw cycling, e.g., Kim and Daniel (1992), although compacted soil-bentonite mixtures may not be as vulnerable to damage. Limited laboratory data indicate that GCLs do not undergo increases in hydraulic conductivity as a result of freeze/thaw. Thus, from the available data, GCLs appear to be superior to CCLs in terms of freeze/thaw resistance.

Wet-Dry Behavior. Wetting and drying of CCLs and GCLs can cause the respective materials to swell or shrink. The main concern with CCLs is that desiccation can lead to cracking and to an increase in hydraulic conductivity.

Available laboratory data indicate that desiccation of wet GCLs does cause cracking, but rehydration of the GCL causes the bentonite to swell and the material to self heal, Kim and Daniel (1992). Thus, GCLs appear to be superior to CCLs in terms of ability to self-heal if the material is wetted, dried, and then rewetted.

Total Settlement Response. Total settlement refers to large scale settlement without significant bending or distortion of the liner system. Clearly, such settlement can be anticipated with MSW landfill covers. Hazardous solid waste (HSW) should be considerably more stable in this regard. Large scale (mass) settlement might also occur in liner systems placed as lateral or vertical expansions. It is believed that GCLs and CCLs would both respond similarly to total settlement and that neither would be damaged if there is no significant bending or distortion.

Differential Settlement Response. LaGatta (1992) studied the effects of differential settlement on the hydraulic conductivity of GCLs. He placed a water-filled bladder in a "false bottom" located beneath the GCL. The GCL was placed over the bladder and was then covered with 600 mm of gravel to simulate cover material. The GCL was flooded with 300 mm of water, and water draining out the bottom of the experimental apparatus was collected for 2 to 4 months, until the flow rate became steady. Then the bladder was incrementally deflated to produce a differential settlement. Boardman (1993) performed similar tests but subjected dry (rather than hydrated) GCLs to differential settlement; the GCLs were hydrated and permeated after the distortion took place in the dry material. The extreme differential settlement caused by the deflated bladders did not produce large increases in hydraulic conductivity for most of the GCLs tested.

Distortion is defined as the differential settlement, Δ, divided by the horizontal distance over which that settlement occurs, L, as shown in Figure 3. Distortion produces tension, which can lead to cracking. It appears from LaGatta's and Boardman's tests that many GCLs can withstand large distortion (Δ/L up to 0.5) and tensile strain (up to 10 to 15%) without undergoing significant increases in hydraulic conductivity. This finding is in sharp contrast to the results for compacted clay, which are summarized in Table 4 as compiled by LaGatta (1992). Normal compacted clay materials cannot withstand tensile strains greater than approximately 0.85% without failing by cracking. Pure bentonite, on the other hand, is reported to have a tensile strain at failure of 3.4%, but LaGatta measured much greater tensile strains without cracking in many GCLs, probably due to the beneficial reinforcing and/or confining effects from the geotextiles or geomembrane of the GCLs. In any case, the available data indicate that GCLs can withstand much greater tensile deformation than CCLs without cracking, which is a favorable characteristic for final covers. GCLs are considered to be superior to CCLs in terms of resistance to damage from differential settlement.

While this same discussion can be applied to the liner system beneath the solid or liquid waste the general situation is not as compelling since soil subgrades should be far more competent than with a body of solid waste. The notable exception, of course, is for vertical and lateral expansions of landfills over existing facilities. Here the situation described above for covers is even further exacerbated due to the high magnitudes of the applied normal stresses.

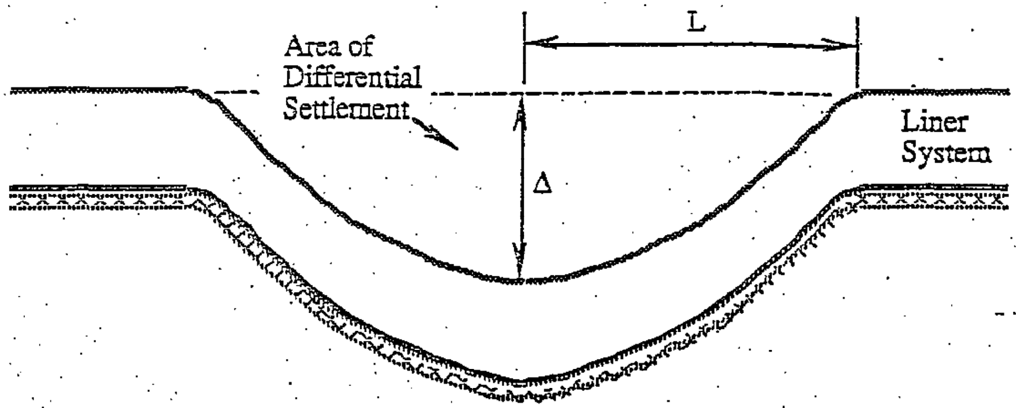


Figure 3. Definition of Liner Distortion "ΔL"

Table 4. Data on tensile strain at failure for compacted clay, LaGatta (1992).

Type or Source of Soil	Water Content (%)	Plasticity Index* (%)	Failure Tensile Strain (%)
Natural Clayey Soil	19.9	7	0.80
Bentonite	101	487	3.4
Illite	31.5	34	0.84
Kaolinite	37.6	38	0.16
Portland Dam	16.3	8	0.14
Rector Creek Dam	19.8	16	0.1
Woodcrest Dam	10.2	Non-plastic	0.18
Shell Oil Dam	11.2	Non-plastic	0.07
Willard Test Embankment	16.4	11	0.20

*Defined as the liquid limit minus the plastic limit per ASTM D4318

Slope Stability Considerations. The mid-plane shear strength of GCLs is obviously sensitive to the water content and type of GCL. Water-saturated GCLs that contain unreinforced, adhesive-bonded bentonite have angles of internal friction for consolidated-drained conditions of approximately 10 degrees. Dry or damp materials are 2 to 3 times higher than water-saturated GCLs. Also, needle-punched and stitch-bonded GCLs have higher strengths, at least in the short term. On-going creep studies of some types of hydrated needle punched GCLs, however, show that linear creep may occur at shear stresses of less than 50% of the short term strength. Whether these trends continue for all needle punched products at all normal stresses is not known. Note that it is possible to lock the needled fibers in place by adhesives or thermal fusion, and thus long term stability is possible. This same study shows that stitch bonded GCLs are very stable under similar conditions. Furthermore, the interface shear strength at the upper and/or lower surfaces of a GCL may be an issue depending on the type of surfaces of the GCL and the nature of the abutting material.

The shear strength of CCLs varies widely. Major factors include type of clay, percentage of clay, water content, density, etc. Thus no comparative conclusions with GCLs can be made.

For stability analyses involving composite liners, one often must consider interfacial shear with an adjacent layer, e.g., a geomembrane. No general statement can be made about equivalency of a GCL to a CCL in terms of interface shear strength because the assessment depends on the specific materials involved, degree to which the bentonite or clay can wet, slope angle, and other site-specific conditions. Even further, slope stability must sometimes be assured against seismic conditions. Again site specific or product specific conditions will be required to make an equivalency assessment.

Vulnerability to Erosion. Erosion resistance may be of concern in final covers if adequate cover soil is not present. With a well-designed and properly maintained cover system, the barrier layer should never be subjected to forces of erosion after the construction phase is over and equivalency should not be an issue. In some cases, however, there may be insufficient cover soil to guarantee that the barrier layer will not be exposed. Because of the presence of erosion-resistant geosynthetic materials in GCLs, most GCLs can potentially be more resistant to erosion than CCLs. However, if a GCL is exposed to erosive forces, the bentonite may be washed out of some products. Thus, equivalency depends upon the specific materials being considered. For many sites, erosion will not be of any concern, e.g., situations with adequate cover soil or for a GCL or CCL underlying a geomembrane.

In general, erosion is not a consideration for either GCLs or CCLs placed as a liner system beneath the waste.

Bearing Capacity (Squeezing). Both CCLs and GCLs must have adequate bearing capacity to support the applied normal stresses. The clay must not squeeze laterally becoming thinner in localized areas under concentrated loads, e.g., wheel loads from construction equipment or maintenance vehicles. Both static and dynamic loads must be resisted depending on the local situation. Even further, if a leak detection system is located beneath the CCL or GCL, fugative particles could clog the drainage layer rendering it ineffective.

Hydrated bentonite in GCLs is not as strong as the typical soils used in constructing CCLs hence GCLs are probably not equivalent to CCLs. However, under most circumstances, a GCL will provide adequate bearing capacity if the material is buried under sufficient soil overburden. Equivalency is heavily dependent upon site-specific conditions and the situation is essentially a design and CQC/CQA consideration and must be viewed as such.

CONSTRUCTION ISSUES

There are a host of construction issues which must be addressed in assessing equivalency of GCLs to CCLs. The best of designs can be defeated if installation is not possible, or is made so difficult so as to engender long term problems.

Puncture Resistance and Resealing. Geosynthetic clay liners are thin and, like all thin geosynthetic materials, are vulnerable to damage from accidental puncture during or after construction. In contrast, thick CCLs cannot be accidentally punctured. Some GCLs have the capability to self-seal around certain punctures, e.g., penetration of the GCL with a sharp object such as a nail. The swelling capacity of bentonite gives GCLs this self-healing capability. Of perhaps greater concern than penetration of the GCL by an object after construction is accidental puncture during construction. For example, if the blade of a bulldozer accidentally punctures the GCL during spreading of cover material, the GCL would probably not self seal in the vicinity of the puncture.

Geosynthetic clay liners will generally not have equivalent puncture resistance to CCLs. However, this does not mean that a GCL cannot meet or exceed the performance objectives of a compacted clay liner. Proper CQC/CQA procedures can be established and implemented to make the probability of puncture during construction extremely low. In final covers, one or two accidental punctures would probably not have a major impact on the overall performance of the barrier layer. In a bottom liner system subjected to a continuous head of leachate, a different conclusion would be drawn about the significance of undetected and unrepaired damage to a GCL from puncture. Ultimately, site-specific conditions and quality assurance procedures will be critical in dealing with the puncture issue and in establishing equivalency of a GCL to CCL for a particular project.

Subgrade Condition Considerations. Compacted clay liners are constructed with heavy equipment. If the subgrade is uneven a CCL can be placed and compacted in a straightforward manner. On the other hand, stones and rocks can cause localized thinning or even puncture of a GCL. If the subgrade contains stones or rocks, the integrity of the GCL will be compromised. Also, in order for the overlapped seams in a GCL to self seal properly, the overlapped panels must be placed on a very smooth and even subgrade. Subgrades with frozen ruts can be particularly troublesome for GCLs and their potential to thin out over the raised ridges is very high. Thus, equivalency of a GCL to a CCL in terms of the effect of subgrade clearly depends on the conditions of the subgrade. This, in turn, depends upon subgrade restrictions placed in the plans and specifications and on the level of CQC/CQA monitoring.

Subgrades must be very carefully prepared for the successful placement o a GCL. It is of significantly less concern when placing a CCL.

Ease of Placement or Construction. A GCL will always be easier to place than a CCL, unless weather conditions are adverse (e.g., constant rain), in which case even a GCL will also be difficult to construct. In general, GCLs are superior to CCLs in terms of ease of placement or construction.

Speed of Construction. GCLs can be placed much more quickly than CCLs. GCLs are superior to CCLs in terms of speed of construction.

Availability of Materials. Suitable clays for construction of a CCL may or may not be available locally, depending on the location of the site. Because GCLs are manufactured materials, they are readily available and can be shipped to a site quickly. The cost of shipment is usually not a large percentage of the total cost of a GCL. Thus, GCLs will always be at least equivalent to CCLs in terms of availability of materials and will be superior to CCLs at sites lacking local sources of suitable clay.

Requirements for Water. Construction water is necessary for many compacted clay soils in order to make a CCL. They are usually placed at a moisture content wet of optimum to achieve the desired low hydraulic conductivity. The total amount of water required to moisten a clay liner can be very large. For example, if a 600 mm thick compacted clay liner were to be constructed over a 5 ha site, and the natural water content of the soil had to be increased 5% to achieve the required moisture conditions, the total amount of water necessary would be approximately 1,500,000 liter. In arid regions, this water may represent a valuable resource, and in some remote locations, it may be very expensive to provide the water. Furthermore, if the only water available is from a local stream which is polluted, the expelled water during consolidation could be a concern in generating leachate or in masking leak detection liquids in double lined systems.

Geosynthetic clay liners do not require construction water and are superior to CCLs in this regard.

Air Pollution Concerns. Air pollution is a subject of great concern in some areas. Construction of CCLs liners tend to be an energy intensive activity with heavy equipment excavating, hauling, processing, spreading, and compacting the soil with repeated passes of heavy compactors. All of this activity adds to air pollution in terms of hydrocarbon emissions from the equipment and air-borne particulate matter (dust). GCLs are factory fabricated, shipped to the site, moved into position by machinery, and then unrolled (sometimes by hand). Air pollution at the factory during GCL manufacturing is generally carefully controlled and monitored. Relatively speaking, the impacts to air quality are less with a GCL than a CCL.

Weather Constraints. Compacted clay liners are difficult to construct when soils are wet, heavy precipitation is occurring, the weather is extremely dry (clay desiccates), the soil is frozen, or the temperature is below freezing. GCLs are difficult to construct during precipitation. Weather constraints during placement generally favor GCLs.

Some, if not all, GCLs must be covered before they hydrate. If a geomembrane will be placed over a GCL, the GCL must be covered almost immediately with the geomembrane. Construction should proceed downgradient with the geomembrane shingled over the edge of the GCL upon the completion of each day's work. If soil is placed over the GCL, backfilling must be kept as close as possible to the exposed edge. Furthermore, the exposed edge should be protected by a temporary membrane at the end of each day's work. The fact that many GCLs must be covered before they are hydrated can be a significant weather constraint for GCLs. CCLs also have weather constraints after placement. CCLs must not be allowed to freeze or desiccate, and wet weather often creates rutting and damage to the surface.

Equivalency in terms of weather constraints must be considered on a site-specific basis, but weather constraints generally favor GCLs over CCLs.

Quality Assurance Considerations. The proper construction of a low-permeability, CCL is a very challenging task. Careful control must exist over materials, moisture conditions, clod size, maximum particle size, surface preparation for a lift of soil, lift thickness, compaction coverage and energy, and protection of each completed lift. Comparatively, CQC/CQA requirements are much less rigorous for GCLs compared to CCLs, but no less critical. In general, while CQC/CQA for a CCL requires a number of relatively sophisticated tests and points of control by very experienced and capable personnel, CQC/CQA for GCLs is more nearly the application of common sense. Far fewer things can go wrong with the installation of a GCL compared to placement and compaction of a CCL. However, testing procedures and observational techniques are well established for CCLs but are not for GCLs. There are major ongoing efforts to establish testing methods for GCLs. ASTM Committee D-35 has recently dedicated an entire subcommittee to this particular material. While it would appear that GCLs are superior to CCLs in terms of ease of quality control, more work needs to be done to establish standard test methods and procedures for GCLs.

SUMMARY OF EQUIVALENCY ASSESSMENT

Clearly an equivalency analysis of GCLs to CCLs will be needed on a site-specific basis. Any broad conclusions that can be drawn will tend to be fairly general. However, a generalized summary of the technical equivalency issues just discussed will be attempted. Tables 5(a) and 5(b) are arranged to parallel the issues in Table 2 and just discussed. Table 5(a) is for liner systems beneath waste materials and Table 5(b) is for cover systems above the waste. Each table is arranged so as to counterpoint GCLs to CCLs in the following manner:

- the GCL is probably superior
- the GCL is probably equivalent
- the GCL is probably not equivalent
- equivalency depends on site specific or product specific conditions

Clearly, the "not equivalent" category of GCLs to CCLs in each table is most important. These issues will be discussed separately. Unfortunately, many issues fall into the "equivalency depends on site specific or product specific conditions" category. They, of course, remain unanswered at least in the generalized sense of this paper.

Table 5(a). Generalized technical equivalency assessment for liners beneath landfills and surface impoundments.

Category	Criterion for evaluation	GCL is probably superior	GCL is probably equivalent	GCL is probably not equivalent	Equivalency depends on site or product
Hydraulic Issues	Steady flux of water		X		
	Steady solute flux		X		
	Chemical adsorption capacity			X	
	Breakout time				
	Water				X
	Solute				X
	Horiz. flow in seams or lifts		X		
	Horiz. flow beneath geomembrane	X			
	Generation of consolidation water	X			
Physical/ Mechanical Issues	Freeze-thaw behavior	X			
	Total settlement		X		
	Differential settlement	X			
	Slope stability				X
	Bearing capacity			X	
Construction Issues	Puncture resistance			X	
	Subgrade condition			X	
	Ease of placement	X			
	Speed of construction	X			
	Availability of materials	X			
	Requirements for water	X			
	Air pollution concerns	X			
	Weather constraints				X
	Quality assurance considerations		X		

Regarding "chemical adsorption capacity" of GCLs in liner systems, equivalency cannot be shown. More of concern, however, is what impact does this issue have on the performance of a given facility. For example, if the liner is a GM/GCL composite the issue might be moot for a properly installed geomembrane. In the short term, absorption by the GCL may be adequate due to very low water flux. In the long term, the adsorption capacity of all liners may eventually be exhausted and is therefore not relevant. If the composite is the primary liner of a double liner system, the leak detection system will handle the liquid and adsorption is not relevant. Thus only when the GCL is used by itself can real concern be expressed, and even then, site-specific conditions are very important.

Regarding "bearing capacity", or squeezing, of hydrated GCLs there is concern for both liners and covers. The hydration of GCLs can be quite rapid. Within a few days, Daniel, et al. (1993) show that 40% moisture content can be attained from soil suction considerations. Concentrated loads from construction equipment and/or maintenance equipment can readily

Table 5(b). Generalized technical equivalency assessment for covers above landfills.

Category	Criterion for evaluation	GCL is probably superior	GCL is probably equivalent	GCL is probably not equivalent	Equivalency depends on site or product
Hydraulic Issues	Steady flux of water		X		
	Breakout time of water				X
	Horiz. flow in seams or lifts		X		
	Horiz. flow beneath geomembranes	X			
	Generation of consolidation water	X			
	Permeability to gases				X
Physical/ Mechanical Issues	Freeze-thaw behavior	X			
	Wet-dry behavior	X			
	Total settlement		X		
	Differential settlement	X			
	Slope stability				X
	Vulnerability to erosion				X
	Bearing capacity			X	
Construction Issues	Puncture resistance			X	
	Subgrade condition			X	
	Ease of placement	X			
	Speed of construction	X			
	Availability of materials	X			
	Requirements for water	X			
	Air pollution concerns	X			
	Weather constraints				X
	Quality assurance considerations		X		

cause squeezing and lateral migration of the hydrated bentonite in some GCL products. GCLs, thin to begin with, can further decrease in their thickness, to the point where the geotextiles are possibly touching one another. This issue must be addressed in design (e.g., to provide suitable thickness for haul roads and access roads) and in strict CQC/CQA procedures during construction.

Regarding "puncture resistance", thin GCLs do not have the same resistance as much thicker CCLs. Although the GCLs can be punctured during construction, careful CQC/CQA should be capable of addressing this potential problem. Further, for final covers, an occasional small puncture may be of little consequence. Indeed, puncture is probably of much greater concern for a bottom liner than for a final cover and of much more concern for single liner systems than for the upper liner in a double liner system. Also, if puncture is of concern, a layer of relatively low permeability soil or waste material may be placed below the GCL to provide a back-up should puncture occur at an isolated location. It should be stated, however, that GCLs enjoy several important advantages over a compacted clay liner which may more than offset its greater vulnerability to puncture.

Regarding "subgrade conditions", the thinness of GCLs is again at issue. With only 7 to 10 mm of thickness of a GCL to begin with, no amount of thinning is tolerable without negatively affecting the water or solute flux calculations provided earlier. Subgrade conditions must be specified as being free from stones, gravel, ruts (particularly when frozen) and all other perturbations in the subgrade material. When placed over the geonet of a leak detection system, rib indentation can cause GCL thinning. This is readily prevented by using the proper separation geotextile between the GCL and geonet, but must be designed accordingly. Thus adverse subgrade conditions can be eliminated as a issue of non-equivalency, but only with proper design and rigorous CQC/CQA procedures.

CONCLUSIONS AND RECOMMENDATIONS

Presented in this paper was an overview of geosynthetic clay liners (GCLs), with the intention of comparing and contrasting them to traditional soil liners. When used for waste containment, such soil liners are usually compacted clay liners (CCLs). However, instead of basing potential equivalency on non-quantifiable issues (like a lack of endorsement by regulatory agencies), three categories of technical issues were evaluated. They were hydraulic, physical/mechanical, and construction categories, each of which had numerous specific issues.

It was seen that there are numerous advantages of GCLs over CCLs. These include better resistance to freeze-thaw, better self healing characteristics in wet-dry conditions, less vulnerability to damage from differential settlement, less consumption of landfill space, easier placement, faster placement, lack of need for local clay materials, less need for construction water (relevant for arid areas), and greater ease of good quality assurance. Geosynthetic clay liners will probably cost less than compacted clay liners for many, and perhaps most, sites. The major disadvantages of GCLs are greater vulnerability to damage from puncture, poor subgrade conditions, lateral squeezing and subsequent thinning of the product. All are potentially controllable by proper design procedures and by rigorous CQC/CQA procedures. While not generally a critical issue, the chemical adsorption capacity of a GCL is lower than a CCL.

As suggested by Tables 5(a) and 5(b), many equivalency issues depend on the particular GCL product selected and the unique site specific conditions. In general, equivalency will have to be evaluated on a case-by-case basis. An important site-specific issue is likely to be slope stability. It may be difficult to provide adequate factors of safety against slope failure on relatively steep slopes that contain certain GCLs. However, designers have a choice of products and, as an option, a variety of reinforcement materials (such as geogrids and geotextiles) available for use, if necessary.

While no general conclusion can be reached about GCL equivalency to a CCL at all sites (either for liner or cover applications) it is expected that GCLs can be shown to provide better or equivalent performance at many sites.

Although GCLs are not without limitations, their favorable properties are sufficiently advantageous that owners, designers, and regulatory officials could give serious consideration to expanded use of GCLs as containment barrier materials. There is a need to reach agreement about the criteria upon which GCLs will be evaluated, and it is hoped that this paper will help to continue the dialogue that will ultimately lead to establishment of agreed upon and appropriate criteria to assess technical equivalency.

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Geosynthetic Clay Liners (GCLs) in Landfill Covers

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ABSTRACT

Low-permeability, compacted clay liners are commonly required as a barrier to water infiltration in landfill covers. A relatively new material, known as geosynthetic clay liner (GCL), has been proposed as an alternative to a compacted clay liner. A GCL has the practical advantages of relatively low cost (approximately \$0.50 to \$0.60 per square foot for a landfill cover, installed), rapid installation with light-weight equipment, and ease of repair. A GCL also has several technical advantages, including greater tolerance for differential settlement and better self-healing characteristics under wet-dry and freeze-thaw conditions. A potentially important disadvantage of the GCL is that, because it is thin, it is more vulnerable to damage from puncture than a compacted clay liner. However, compacted clay liners are not without their problems, too, and designers, as well as regulators, of final landfill covers are encouraged weigh the advantages and disadvantages of the various materials before reaching a decision about the best material to use for a particular landfill.

Most regulatory agencies require that compacted clay, or the equivalent, be used as a barrier to water infiltration in final covers. Typically, a 1- to 2-ft-thick layer of compacted clay having a hydraulic conductivity (coefficient of permeability) $\leq 1 \times 10^{-7}$ cm/s is required. To achieve regulatory approval, an applicant who proposes to use a GCL rather than a compacted clay liner may be required to demonstrate that the GCL will perform in an equivalent manner to a compacted clay liner. If the GCL can be shown to be equivalent in terms of meeting performance objectives, a basis for regulatory approval is established.

The objectives of this paper are: (1) to provide an introduction to GCLs for those who may be unfamiliar with this lining material; (2) to summarize the potential applications of GCLs to landfill covers; (3) to examine the relative advantages and disadvantages of GCLs compared to compacted clay liners; and (4) to provide a generic assessment of performance equivalency of GCLs compared to low-permeability, compacted clay barriers. The fourth item will comprise the bulk of the paper. The conclusion is drawn that geosynthetic clay liners can be shown to provide equivalent performance to low-permeability, compacted clay liners for many landfill sites. The key issues concerning equivalency are ability to limit percolation of water through the barrier, permeability to gas, slope stability, and puncture resistance.

INTRODUCTION TO GEOSYNTHETIC CLAY LINERS

The Material

Geosynthetic clay liners (GCLs) are thin "blankets" of bentonite clay attached to one or more geosynthetic materials (e.g., geotextile or geomembrane). Bentonite is a unique clay mineral with very high swelling potential and water absorption capacity. When wetted, bentonite is the least permeable of all naturally-occurring, soil-like minerals. Bentonite is also a chemically stable mineral that has undergone complete weathering and will last, in effect, forever.

Geosynthetic clay liners are manufactured by laying down a layer of dry bentonite, approximately 1/4-inch thick, on a geosynthetic material and attaching the bentonite to the geosynthetic material. Two general configurations are currently employed in commercial processes: bentonite sandwiched between two geotextiles (Fig. 1a) or bentonite glued to a geomembrane (Fig. 1b). The primary purpose of the geosynthetic component or components is to hold the bentonite together in a uniform layer and permit transportation and installation of the material without losing bentonite or altering the thickness of the bentonite. However, the geosynthetic components may serve other important purposes, as well, such as adding tensile or shear strength to the material.

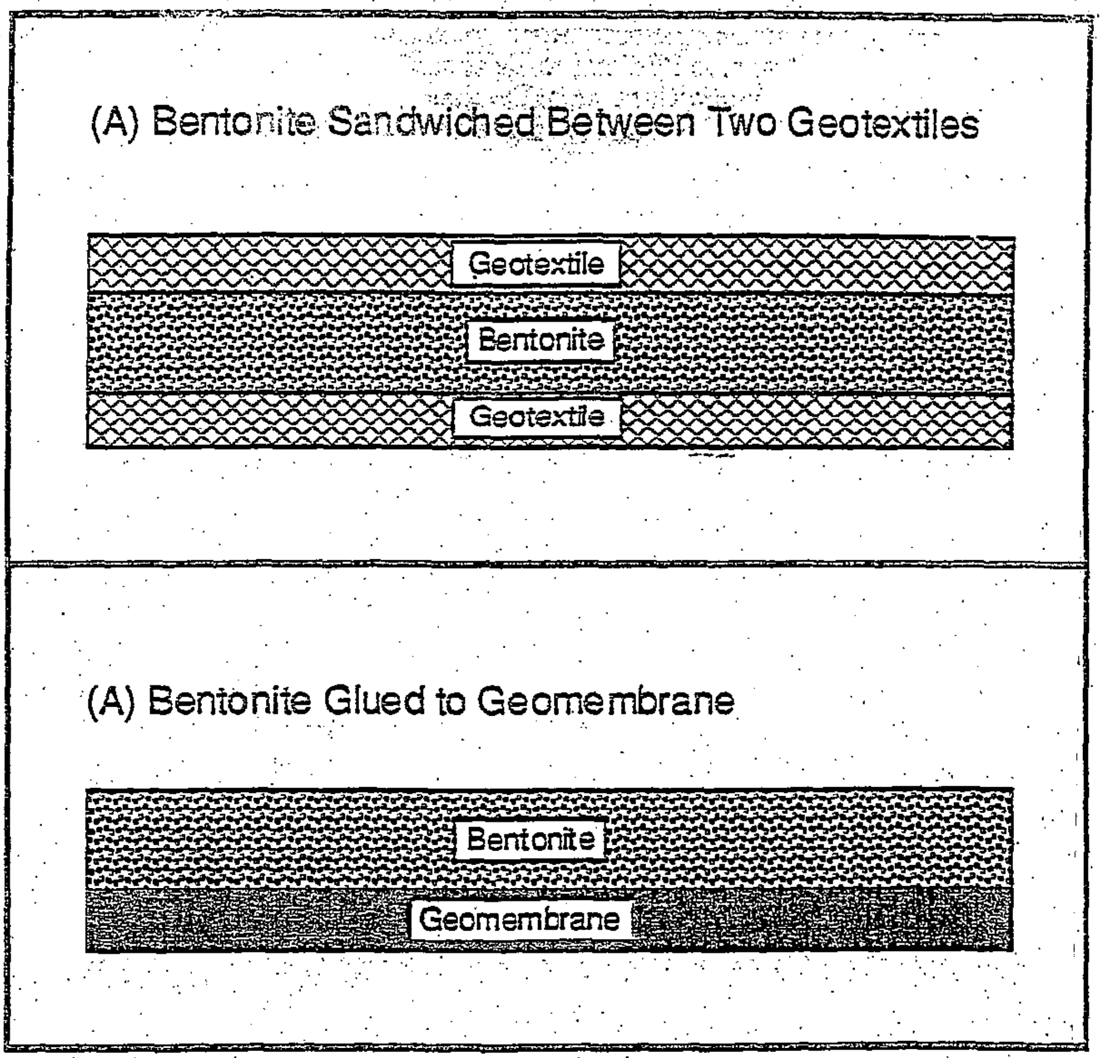

Figure 1. General Configuration of Geosynthetic Clay Liners.

The bentonite component of a manufactured GCL is essentially dry, and there are open voids between bentonite granules in the manufactured material. When the bentonite is hydrated with water (for example, by imbibing water from underlying or overlying soils), the bentonite swells and the voids between bentonite granules close. The swelling action of bentonite is crucial to attainment of low permeability.

Geosynthetic clay liners contain approximately 1 pound per square foot of high-quality sodium bentonite that has a hydraulic conductivity (coefficient of permeability) of approximately 1×10^{-9} cm/s or less. *Continuous gravity percolation under unit hydraulic gradient through a material with a hydraulic conductivity of* 1×10^{-9} cm/s would result in an infiltration rate of 0.01 inches per year, or approximately 1 inch every 100 years. For landfill covers, an intact GCL may *be considered essentially impermeable to water.*

Geosynthetic clay liners were first manufactured in the early 1980's and were initially used for foundation water proofing and for sealing water retention structures. Geosynthetic clay liners were first used for landfill liners in 1986. Since 1986, geosynthetic clay liners have been used for a variety of lining applications and also in several final cover systems for hazardous wastes, radioactive wastes, and non-hazardous solid wastes.

Commercial Products

Four geosynthetic clay liners are currently manufactured: Bentofix®, Bentomat®, Claymax®, and Gundseal®. The GCLs fall into the broad categories shown in Fig. 1 as follows:

- Bentonite sandwiched between two geotextiles: Bentofix®, Bentomat®, and Claymax®
- Bentonite mixed with an adhesive and glued to a geomembrane: Gundseal®.

The GCLs are sketched in Fig. 2. Bentofix® and Bentomat® consist of bentonite sandwiched between a woven and non-woven geotextile that are needle-punched together. Claymax® 200R consists of bentonite mixed with glue and sandwiched between two woven geotextiles. Claymax® 500SP consists of bentonite mixed with glue and sandwiched between two woven geotextiles that are sewn together. The purpose of stitching the two geotextiles together is to provide additional internal reinforcement and greater shear strength. With all the geotextile-encased GCLs, special geotextiles can be selected to "custom design" the GCL to a particular application. Gundseal® is made by mixing bentonite with an adhesive and attaching the bentonite layer to a polyethylene geomembrane. Gundseal® can be supplied with high density polyethylene (HDPE) or very low density polyethylene (VLDPE), and the geomembrane can be either smooth or textured.

All GCLs are manufactured in panels with widths of approximately 13 to 17 ft and lengths of approximately 75 to 200 ft. The panels are placed on rolls at the factory and are unrolled at the time of installation. The weight of the roll varies, depending on size and materials, from about 1,400 to 4,000 pounds.

The panels are typically overlapped 3 to 12 in. during installation and are said to be "self sealing" at the overlap. A sketch of the overlapped zones is shown in Fig. 3. With geotextile-encased, needle-punched GCLs, sodium bentonite is placed along the overlap (Fig. 3a) at a rate of approximately 0.25 lb/ft. The bentonite penetrates the pores of the geotextiles and is said by the manufacturers to cause the materials to self seam when the bentonite hydrates. With geotextile-encased, adhesive-bonded GCLs, no additional bentonite is needed (Fig. 3b). The material is said to self seal upon hydration at the overlaps through expansion and "oozing" of bentonite out through the openings of the geotextile in the overlap area.

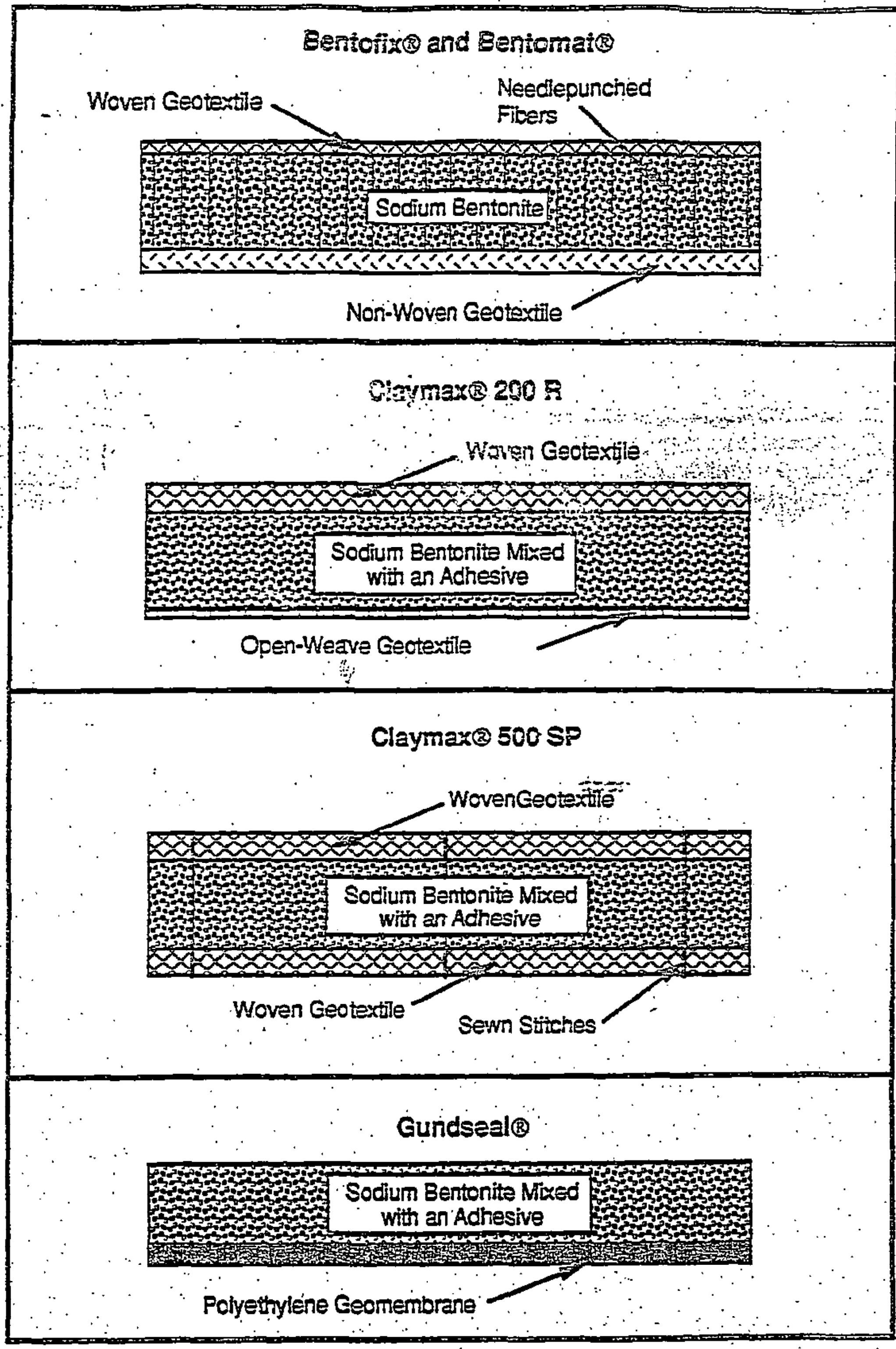

Figure 2. Commercially-Produced Geosynthetic Clay Liners.

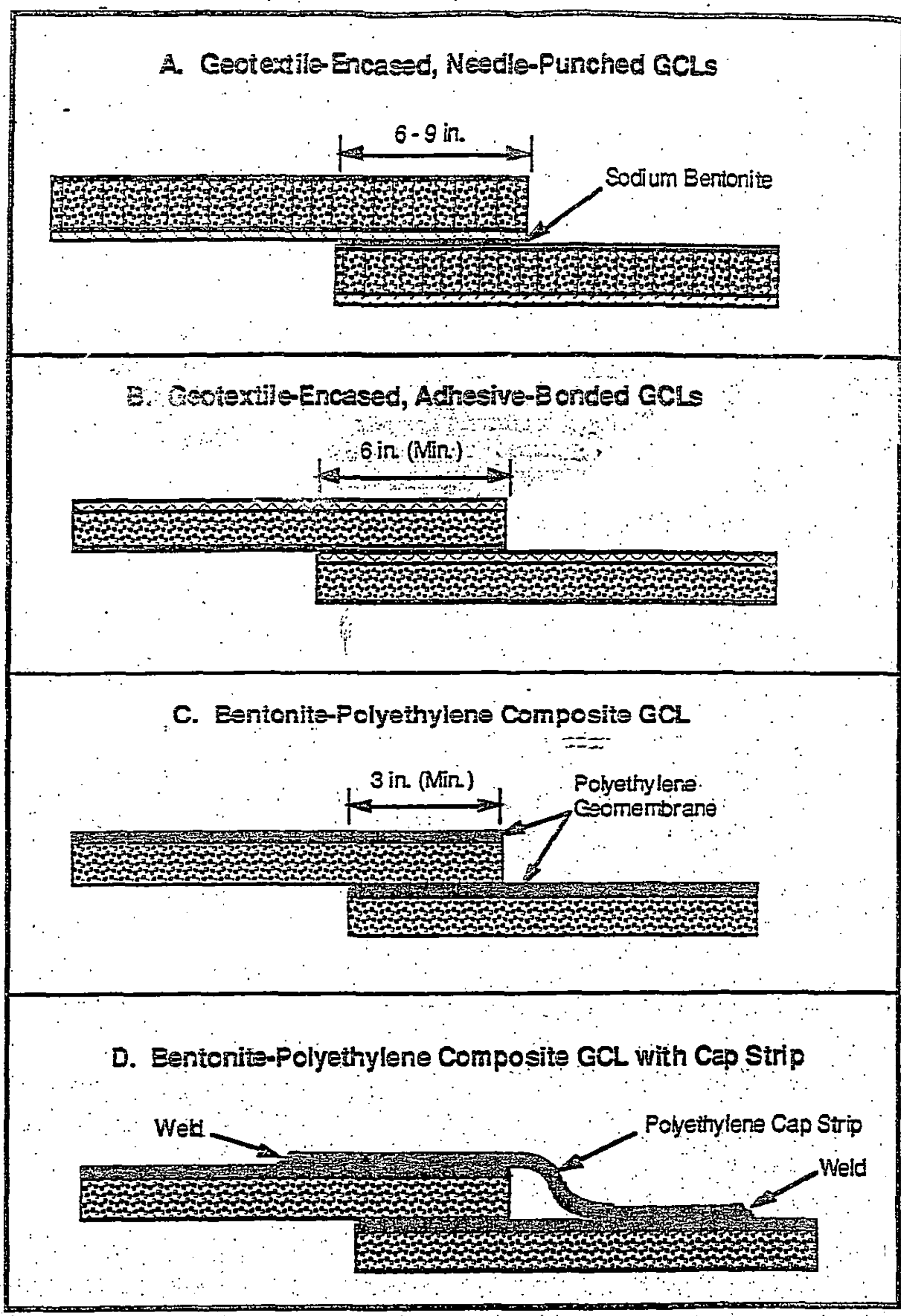

Figure 3. Overlapped Zone of Geosynthetic Clay Liners.

With GCLs containing a geomembrane, the GCL can be placed with the bentonite facing upward (Fig. 2) or, as shown in Fig. 3c and 3d, downward. If the GCL will be used by itself as a composite geomembrane-clay liner, the geomembrane would face upward. If a separate geomembrane is to be placed on the GCL, the bentonite would face upward. The material is said to be self sealing at overlaps with no need for any mechanical seam at the overlap (Fig. 3c). However, if one wants to form a continuous geomembrane out of the geomembrane component of the GCL, a cap strip can be welded over the overlap (Fig. 3d).

Potential Uses of Geosynthetic Clay Liners in Final Cover Systems

Geosynthetic clay liners can be used in final cover systems in several ways, as shown in Fig. 4. One choice (Fig. 4a) is to use the GCL by itself as a barrier to water infiltration. The GCL would be buried below a layer of protective soil. As indicated earlier, the bentonite component is expected to be essentially impermeable to water after it is has been hydrated, assuming that the GCL withstands the potentially damaging effects of wet-dry cycles and differential settlement (discussed later). One possible problem with using a GCL by itself as a barrier layer is that the dry bentonite is initially highly permeable to landfill gas – the bentonite would have to absorb water, hydrate, and swell before the bentonite becomes an effective barrier to gas migration, and the bentonite could not be allowed to dry out because the bentonite would again become permeable to landfill gas. At extremely arid sites, there may not be adequate water available to hydrate the bentonite to the extent that is necessary in order for the GCL to have a low permeability to gas. However, for those GCLs that contain a geomembrane, the geomembrane itself provides a barrier to gas migration. In addition, a barrier to gas migration within the final cover may or may not be a design consideration, depending on site-specific considerations.

The second potential use of a geosynthetic clay liner in a final cover system is in conjunction with a geomembrane (Fig. 4b) to form a composite geomembrane/GCL liner. The composite could either be formed by using a GCL that contains a geomembrane or by separately constructing a geomembrane on top of a GCL. By placing clay under the geomembrane, the clay serves to seal off any imperfections in the geomembrane, e.g., pinholes or defects in seams, and to help in providing an extremely effective composite barrier to infiltration of water. The geomembrane would protect the underlying GCL from wet-dry cycles and would serve as a gas barrier for those periods when the bentonite component of the GCL is relatively dry. The main advantages of a separately-constructed geomembrane are that a separate polyethylene geomembrane liner could be seamed with the most advanced welding equipment available, which is microprocessor-controlled, dual-track, hot wedge welding equipment, or that some other type of geomembrane besides polyethylene could be used, if desired. If a bentonite-polyethylene composite GCL is used and the polyethylene components are to be seamed at overlaps, a cap strip is typically placed over the overlapped region and the edges of the cap strip are welded with fillet extrusion welding apparatus (Fig. 3d). However, because water flow through non-welded seams is expected to be negligible, the author encourages designers not to use cap strips over overlapped panels unless there is a good reason to do so.

A third option is to sandwich the GCL between two geomembranes (Fig. 4c). One or both geomembranes would be separately installed, depending upon the GCL material employed. The advantage of this design is that even less percolation of water through the barrier would occur. In fact, the bentonite component would become wetted only around minor imperfections in a geomembrane or its seams, where the bentonite would serve to seal off the leakage through the imperfection. This type of design approach, with a triple-composite liner, has rarely (if ever) been used for final covers over solid waste landfills and would be considered an extreme design for those facilities requiring extraordinary protection from water percolation or gas migration through the final cover.

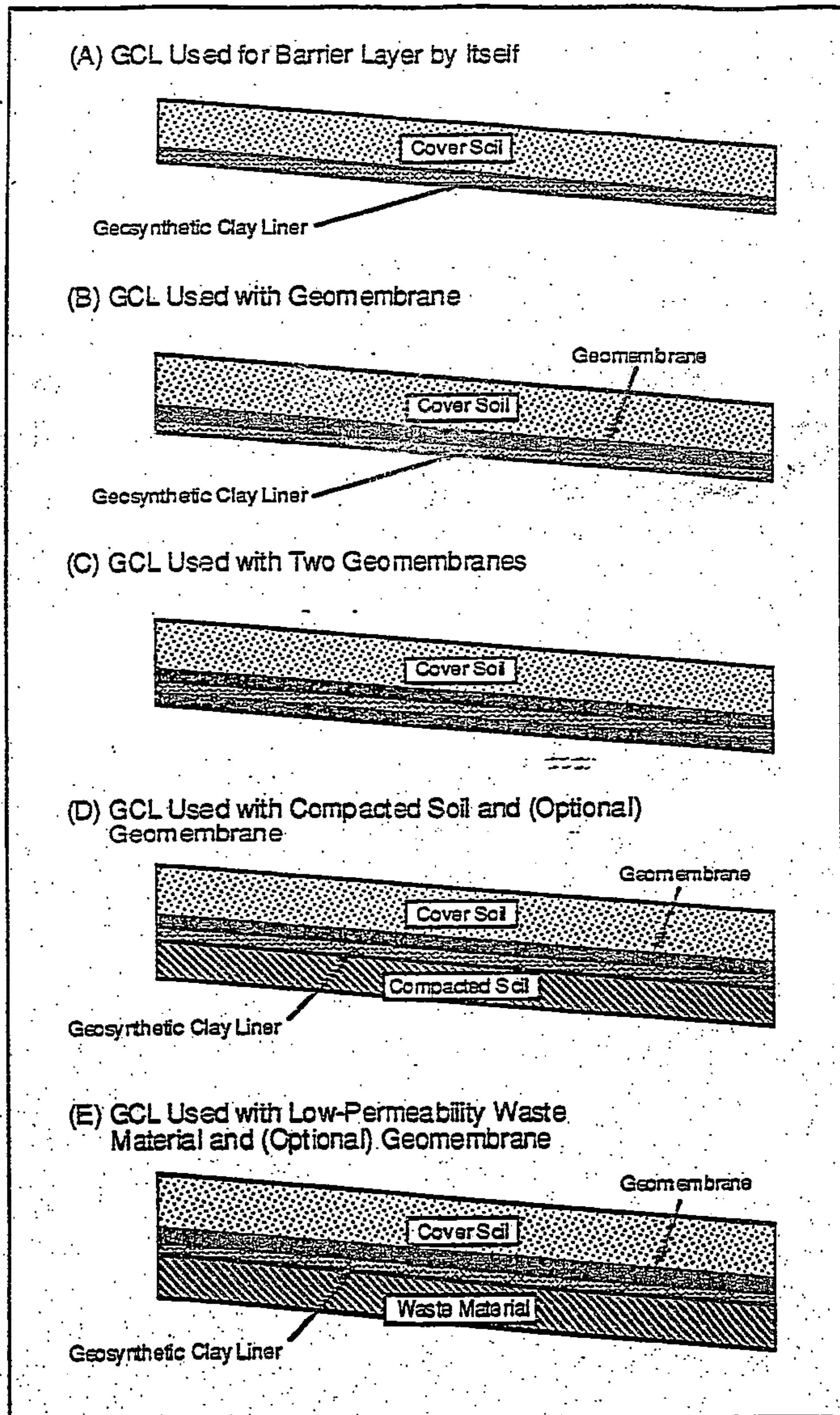

Figure 4. Potential Uses of Geosynthetic Clay Liners in Landfill Covers.

A fourth option is to place the GCL on top of a low-permeability, compacted soil liner (Fig. 4d), possibly with a geomembrane placed on top of the GCL (Fig. 4d). This design adds redundancy of materials and enables one to provide a very high degree of protection in the final cover system. In such cases, the GCL may replace part of a conventional compacted clay liner, or the low-permeability soil component may have a hydraulic conductivity that is greater than the usual 1×10^{-7} cm/s (i.e., use of the GCL lessens the need for extremely low permeability in the underlying soil barrier layer).

A fifth option is to place the GCL on top of a low-permeability, re-used waste material (Fig. 4e), possibly with a geomembrane placed on top of the GCL (Fig. 4e). This design adds redundancy of materials and enables one to make productive use of waste materials. An example of a waste material that might be considered is paper industry sludges (Maltby and Eppstein, 1993).

ENGINEERING PROPERTIES OF GCLs

Hydraulic Conductivity

In general, the hydraulic conductivity of the bentonite component of GCLs varies between about 1×10^{-10} and 1×10^{-8} cm/s, depending on the confining stress. The higher the compressive stress, the lower the hydraulic conductivity. There are some differences between the hydraulic conductivities of the various GCLs, but, except for bentonite-geomembrane composite GCLs (for which the geomembrane will significantly reduce the overall hydraulic conductivity), the differences do not appear to be very large. The available data are summarized by Schubert (1987), Daniel and Estornell (1990), Scheu et al. (1990), Daniel (1991), Eith et al. (1991), Shan and Daniel (1991), Estornell and Daniel (1992), Grube (1992), Daniel et al. (1993), and Daniel and Boardman (1993).

For a final cover system, a confining stress on the order of 200 psf to 600 psf is a reasonable range. Laboratory hydraulic conductivity tests performed on backpressure-saturated test specimens in flexible-wall permeameters indicate that the hydraulic conductivity of the bentonite component of GCLs in this range of compressive stress is approximately 1 to 4×10^{-9} cm/s. Estornell and Daniel (1992) measured the hydraulic conductivity of GCLs in large tanks. The tests were specifically set up to simulate conditions of low overburden stress that are typical of final cover systems and to test very large specimens with overlaps. Of the 10 tests for which hydraulic conductivities were measured, the average value was 4.6×10^{-9} cm/s (normal averaging) or 2.2×10^{-9} (logarithmic averaging). Based on all the data, a reasonable assumption is that a GCL can be supplied with a hydraulic conductivity for a landfill cover application less than 1 to 5×10^{-9} cm/s.

Studies of the hydraulic properties of overlapped seams performed by Estornell and Daniel (1992) indicate that the overlapped seams in GCLs self seam in the manner described by the manufacturers. For geotextile-encased, needle-punched GCLs with additional bentonite along the overlap, the bentonite appears to swell upon hydration and plug voids in the geotextiles present in the overlap. For the geotextile-encased, adhesive-bonded GCLs that have been tested, the bentonite within the GCL appears to ooze out through the openings in the geotextile and to allow the material to self seal. For bentonite-geomembrane composite GCLs, the bentonite swells upon hydration, seals at the bentonite-polyethylene interface, and effects self-seaming at the overlap. Thus, based on the available data, it is reasonable to assume that with proper quality control in the field, seams can be installed that will self-seal.

Strength

Internal Shear Strength. The internal shear strength of GCLs has been determined by the manufacturers and various organizations and testing laboratories. "Internal shear strength" refers to the strength of the material when sheared through the mid-plane of the bentonite. The author and his students at the University of Texas have performed independent tests, which are described below.

Direct shear tests were performed on square specimens that measured approximately 2.5 in. in length and width. Test specimens were cut from parent material, set up in a direct shear apparatus, and subjected to the desired normal load. For tests on water-saturated specimens, the specimens were then soaked with water and allowed to equilibrate; about 3 weeks were required before swelling ceased. Test specimens were sheared very slowly with failure occurring in 3 to 7 days. Results on water-saturated GCLs are summarized in Figure 5.

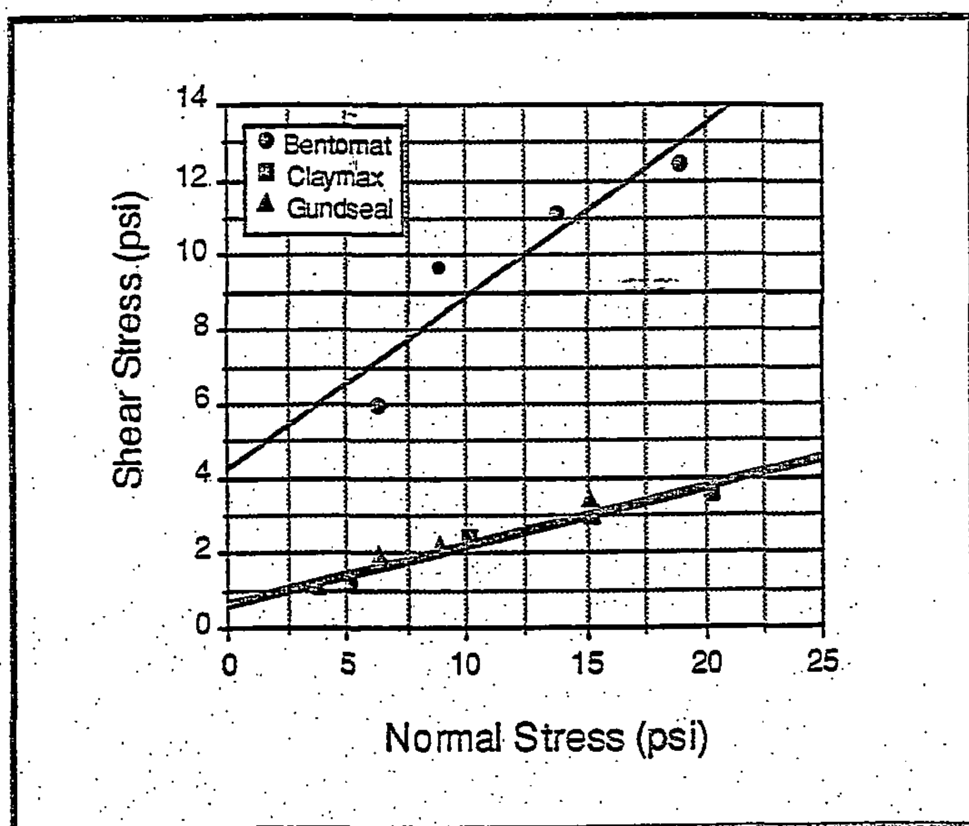

Figure 5. Results of Direct Shear Tests on Fully Hydrated GCLs.

The failure envelopes shown in this figure were determined from linear regression analysis, which yielded the following results:

Geosynthetic Clay Liner	Effective Cohesion (psi)	Angle of Internal Friction (Degrees)
Bentomat®	4.4	29
Claymax®	0.6	9
Gundseal®	1.2	8

The reader is reminded that these results are for completely water-saturated bentonite -- if the bentonite is encased between two geomembranes, it is unlikely that the bentonite will become saturated throughout.

Careful examination of the low-normal-stress region shows that the failure envelope is distinctly curved. This curvature is significant because it means that the materials are stronger at low compressive stresses (such as experienced in final covers) than other situations. In studies recently completed at the University of Texas, tilt-table tests were performed. Samples of GCL materials that measured 12 in. by 12 in. were set up on a tilt table, loaded with a steel plate, placed in a water bath, and allowed to fully hydrate. Then the table was slowly tilted over a period of several weeks until sliding occurred. The tilt table and direct shear data for one GCL (Gundseal®) are shown in Fig. 6. The failure envelope is obviously curved. Figure 7 presents the relationship between angle of internal friction and normal stress. For landfill covers, a typical range of normal stress is approximately 200 to 600 psf. Although the data are presented for only one GCL, similar trends are expected for other GCLs. Designers should exercise care in evaluation of shear strength data to ensure that the proper parameters for the conditions expected in the field are utilized in design.

Dry bentonite is much stronger than water-saturated bentonite. For dry GCLs or slightly damp GCLs, the angle of internal friction (even for the materials that are not internally reinforced) is approximately 35°. It is only if the material is hydrated that bentonite becomes weaker.

For those GCLs that are needle-punched or sewn together, the internal reinforcement of the GCL makes the material's internal shear strength much less sensitive to the strength of the bentonite contained between the attached geotextiles. However, the reader is cautioned that for landfill covers, the GCL may be exposed to prolonged shearing stresses for periods of years, decades, or even centuries, and that the long-term shearing resistance should be carefully considered.

Interfacial Shear Strength. "Interfacial shear strength" refers to the shearing strength between two adjacent components of a liner or cover system. The GCL may be placed against soil, a geomembrane, or a geotextile. Because the range of possible materials at an interface is unlimited, the actual interfacial shearing properties are usually determined on a project-specific basis. It is the author's experience that the internal shear strength will often govern the design because, with proper selection of materials, relatively high interfacial strengths can usually be obtained.

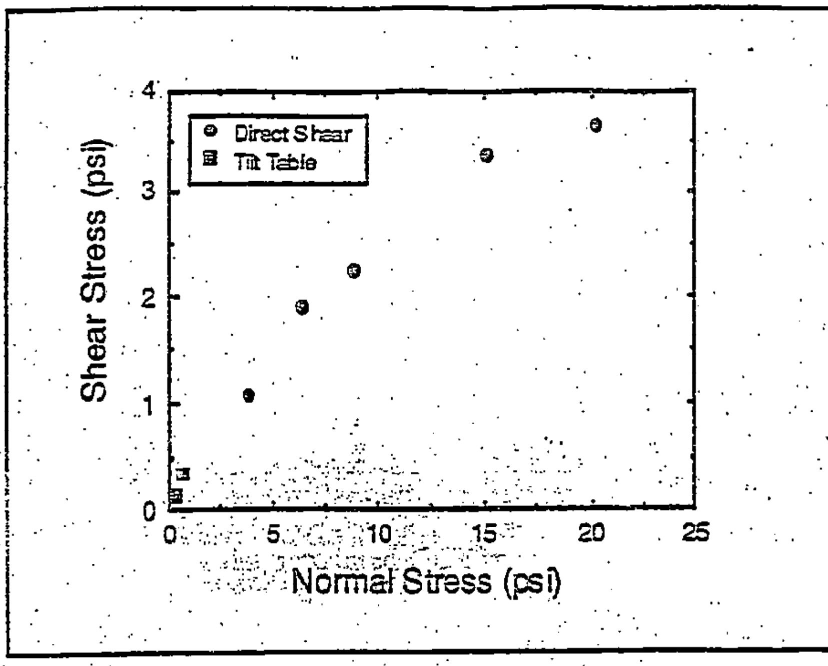

Figure 6. Failure Envelope for One Water-Saturated GCL Including Results of Tilt Table Tests.

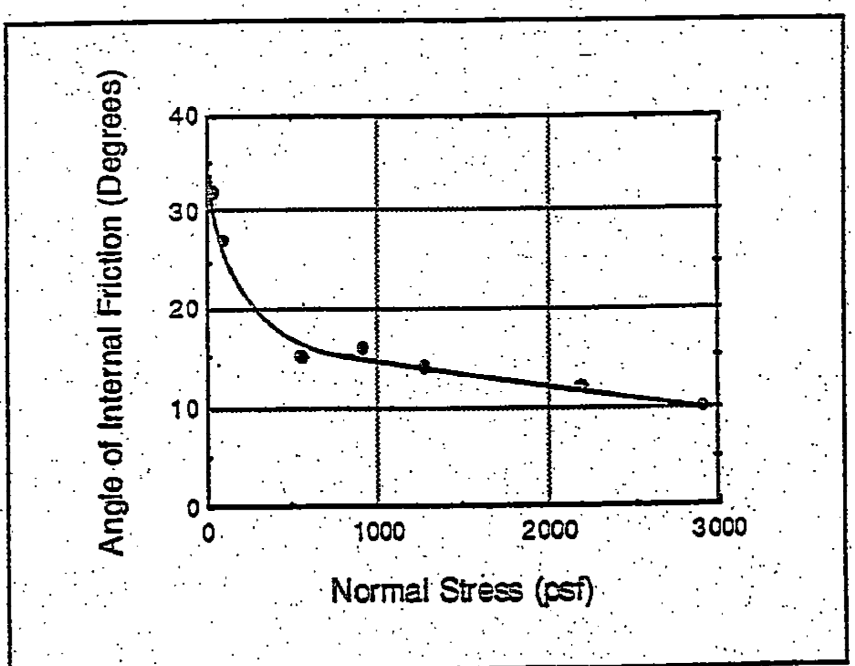

Figure 7. Influence of Normal Stress on Internal Shear Strength of One Water-Saturated GCL.

Tensile Strength

The tensile strength of a GCL is derived almost exclusively from the tensile strength of the geosynthetic components. For those GCLs that are constructed from unmodified geosynthetics (i.e., no needle-punching or other alteration of the parent geosynthetic material), the tensile strength of the GCL may be taken as the tensile strength of the geosynthetic components. For those GCLs whose geosynthetic components have been altered during the manufacturing of the GCL (i.e., needle-punched or sewn GCLs), tensile strength can be measured by performing a wide-width tensile test on the GCL material itself. Data on tensile properties of GCLs is available from the manufacturers.

Durability

Puncture Resistance. Shan and Daniel (1991) studied the effects of punctures on a geotextile-encased, adhesive-bonded GCL. The manufacturers of other GCL products have developed similar data for their particular products. The effects of punctures on the hydraulic conductivity of the GCL were studied by drilling or cutting circular holes into the dry GCL, setting the punctured GCL up in flexible-wall permeameters, and permeating the GCL slowly until steady flow was achieved. Results are summarized in the following table:

Diameter of Puncture	Hydraulic Conductivity (cm/s)
No Punctures	2×10^{-9}
0.5 in.	3×10^{-9}
1 in.	5×10^{-9}
3 in.	$> 1 \times 10^{-4}$

Small (≤ 1 in. diameter) punctures made in the dry material self-sealed upon hydration of the bentonite. These tests illustrate the self-healing capability of bentonite. Each particular GCL has a different capacity to self-heal punctures. However, all GCLs are capable of self healing small punctures in the dry GCL when the bentonite is hydrated. It should be emphasized that these tests were performed under carefully controlled conditions in which no material other than bentonite was allowed to fill the puncture. In the field, other materials may fill large punctures. Although GCLs have some capability to self-seal if punctured, there are clearly limitations in the size of puncture that could self seal in the field.

Desiccation. Concern has been expressed that the bentonite component of a GCL may swell when hydrated but may later dry out, shrink, crack, and lose its impermeability. Shan and Daniel (1991) investigated the healing capability of one geotextile-encased, adhesive-bonded GCL that was subject to wet-dry cycles. Samples of the GCL were permeated in a flexible-wall permeameter, removed from the permeameter, and allowed to air dry with a small vertical stress applied to the specimens. All specimens exhibited severe cracking upon drying. The specimens were then set back up in a flexible-wall permeameter, slowly rehydrated, and then repermeated. There was no change in hydraulic conductivity from the initial value of 2×10^{-9} cm/s, even after three wet/dry cycles. These tests reinforce the fully reversible shrink/swell nature of bentonite and suggest that any desiccation cracks will self-heal when the bentonite is hydrated.

In research recently completed at the University of Texas (Boardman, 1993), large samples of GCLs (with and without overlaps) were buried under 2 ft of gravel and subjected to a wet-dry cycle that simulates severe conditions that might occur in a final cover for a landfill. The GCLs were set up in the tanks, hydrated with water until a steady hydraulic conductivity was measured, and then severely desiccated by draining away the water on top of the GCL and circulating heated air into the gravel that was placed over the GCL. The heated air caused severe desiccation cracking in the GCLs. However, when the GCLs were rehydrated, the bentonite quickly swelled and the hydraulic conductivity eventually returned to the original, extremely low value. Thus, it appears from the available data that GCLs have an excellent capacity to self seal from desiccation-induced cracking. Geosynthetic clay liners probably possess much greater ability to self seal than conventional compacted clay liners.

Freeze/Thaw. Compacted clay liners are known to be vulnerable to damage from freezing. When water in soil freezes, the water expands, and when the water thaws, the water contracts. This expansion and contraction causes small cracks to appear in the soil and causes other alterations in the soil structure that tend to increase hydraulic conductivity.

Shan and Daniel (1991) subjected a geotextile-encased, adhesive-bonded GCL to freeze/thaw. A test specimen was set up in a flexible-wall permeameter, hydrated with water, and permeated until a steady hydraulic conductivity was obtained. Then the specimen was removed from the flexible-wall permeameter and subjected to five freeze/thaw cycles at constant water content. The specimen was repermeated, and it was found that the hydraulic conductivity did not change. Similar results have been obtained by commercial testing laboratories for other GCL products. Available data indicate that the high shrink-swell capability of bentonite gives bentonite the ability to self-heal if any alteration occurs from freeze/thaw cycles. Geosynthetic clay liners appear to have a much better capacity to remain undamaged after freeze-thaw than conventional compacted clay liners.

PERFORMANCE ASSESSMENT

Many regulatory agencies have traditionally required a low-permeability, compacted clay liner (or the equivalent) as the primary hydraulic barrier within landfill covers. The thickness of a compacted clay liner typically ranges from 1 to 2 ft (occasionally up to 3 to 4 ft), and the maximum allowable hydraulic conductivity is typically 10^{-7} cm/s. If one wishes to substitute a GCL for a compacted clay liner, one must usually demonstrate that the GCL will be equivalent in terms of meeting performance objectives. Neither federal nor state regulations mention the criteria by which equivalency should be evaluated. At the present time equivalency must be evaluated on a case-by-case basis using criteria that are not very well defined. The lack of accepted criteria is perhaps the single greatest problem that the landfill designer and owner face in seeking regulatory approval for substitution of a GCL for a compacted clay liner.

One should not really think of a geosynthetic clay liner as being equivalent to a compacted clay liner. Indeed, a 1/4-in.-thick layer of bentonite could not possibly be equivalent to a much thicker layer of compacted clay in all respects. The critical issue is whether substitution of an alternative material such as a GCL for the more traditional compacted clay liner in a landfill cover will meet or exceed the performance objectives of the compacted clay liner. If the GCL will meet or exceed the performance objectives, then it should be considered that equivalency has been established.

Differences Between CCLs and GCLs

Some of the differences between compacted clay liners and geosynthetic clay liners are listed in Table 1.

Table 1 - Differences Between GCLs and Compacted Clay Liners.

Characteristic	Geosynthetic Clay Liner	Compacted Clay Liner
Materials	Bentonite, Adhesives, Geotextiles, and Geomembranes	Native Soils or Blend of Soil and Bentonite
Thickness	Approximately 1/2 inch	Typically 1 to 2 ft
Hydraulic Conductivity	≤ 1 to 5×10^{-9} cm/s	$\leq 1 \times 10^{-7}$ cm/s
Speed and Ease of Construction	Rapid, Simple Installation	Slow, Complicated Construction
Ease of Quality Assurance (QA)	Relatively Simple, Straight-Forward, Common-Sense Procedures	Complex QA Procedures Requiring Highly Skilled and Knowledgeable People
Vulnerability to Damage During Construction as a Result of Desiccation	GCLs Are Essentially Dry; GCLs Cannot Desiccate during Construction	Compacted Clay Liners Are Nearly Saturated; Can Desiccate during Construction
Availability of Materials	Materials Easily Shipped to Any Site	Suitable Materials Not Available at All Sites
Cost	Typically \$0.50 to \$0.60 per Square Foot for a Large Site	Highly Variable -- Estimated Range: \$0.50 to \$5.00 per Square Foot
Experience	Limited Due to Newness	Has Been Used for Many Years

Some of the potentially important (depending upon specific application) relative advantages of CCLs and GCLs may be summarized as follows:

- Key advantages of compacted clay liners (CCLs):
    - Many regulatory agencies require CCLs -- use of another type of liner may require time-consuming demonstration of equivalency to a CCL;

- A CCL is a logical choice if large quantities of suitable clay are available locally;
- The large thickness of CCLs makes them virtually puncture proof;
- The large thickness of CCLs and the fact that they are constructed of multiple layers makes them relatively insensitive to small imperfections in any one layer;
- There is a long history of use of CCLs;
- Quality assurance procedures are reasonably well established for CCLs.

- Key advantages of geosynthetic clay liners (GCLs):
  - Small thickness of GCLs leads to low consumption of landfill space;
  - Construction of GCLs is rapid and simple;
  - GCLs can be shipped to any location -- their use is not dependent upon local availability of materials;
  - Heavy equipment is not needed to install a GCL, which is very helpful for final covers underlain by compressible waste (where compaction with heavy equipment is difficult);
  - Installation of a GCL requires less vehicular traffic and less energy use than placement and compaction of a CCL -- this also leads to less air pollution with a GCL;
  - Some inclement weather delays (e.g., freezing temperatures) that stop construction of CCLs are not a problem with GCLs;
  - Construction water is not needed with a GCL, which can be critical in arid areas where water resources are scarce;
  - Because a GCL is a manufactured material, a consistent and uniform material can be produced;
  - Because GCLs are manufactured materials, specialized performance properties can be determined and need not be repeatedly re-determined;
  - GCLs can accommodate large differential settlement;
  - Quality assurance is simpler for a GCL compared to a CCL;
  - GCLs are more easily repaired than CCLs;
  - GCLs can probably better withstand freeze/thaw and wet/dry cycles than CCLs;
  - GCLs are not vulnerable to desiccation damage during construction.

<u>Criteria for Performance Assessment and Equivalency Analysis</u>

Three broad issues may be addressed when one considers the equivalency of a GCL to a CCL:

1. Hydraulic issues;
2. Physical/mechanical issues;
3. Construction issues.

The specific technical issues that might have to be addressed for a particular site are listed in Table 2. For completeness, the issues are identified for both bottom liners and final covers. Only final covers are considered in the succeeding discussion.

Table 2 - Potential Equivalency Issues.

Category	Criterion for Evaluation	Possibly Relevant for: Liners	Covers
Hydraulic Issues	Steady Flux of Water	X	X
	Steady Solute Flux	X	
	Chemical Adsorption Capacity	X	
	Breakout Time:		
	-Water	X	X
	-Solute	X	
	Production of Consolidation Water	X	X
	Permeability to Gas	X	X
Physical/ Mechanical Issues	Freeze-Thaw	X[1]	X
	Wet-Dry		X
	Total Settlement	X[2]	X
	Differential Settlement	X[2]	X
	Slope Stability	X[3]	X
	Erosion		X
	Bearing Capacity	X	X
Construction Issues	Puncture Resistance	X	X
	Subgrade Condition	X	X
	Ease of Placement	X	X
	Speed of Construction	X	X
	Availability of Materials	X	X
	Requirements for Water	X	X
	Air Pollution Effects	X	X
	Weather Constraints	X	X
	Quality Assurance	X	X

[1]Relevant only until liner is covered sufficiently to prevent freezing
[2]Settlement of liners usually of concern only in certain circumstances, e.g., vertical expansions
[3]Stability of liner may not be relevant after filling, if no permanent slope remains

Hydraulic Issues. Hydraulic issues are the easiest to quantify. The criteria, which are discussed separately, include steady water flux, time to initiate release of water from the base of the liner ("breakout time"), production of consolidation water, and air permeability.

1. Steady Flux of Water

Water flux is defined as the volume of flow across a unit area in a unit time. For a barrier in a final cover system, water flux is equal to the rate of percolation of water through the barrier layer.

Water flux is usually analyzed based on the long-term, steady state water flux. The flux of water (v) through an individual layer of porous material is defined from Darcy's law as:

$$v = k \frac{H + T}{T} \qquad (1)$$

where k is the hydraulic conductivity, H is the depth of liquid ponded on the liner, and T is the thickness of the liner. The water pressure on the base of the liner is assumed to be atmospheric pressure in Eq. 1.

Equation 1 is applicable only for flow through the bentonite component of a GCL; if the GCL contains a geomembrane, water flux will be controlled by water vapor diffusion through the geomembrane component. The geomembrane component, if present, should be considered in the equivalency analysis and in computation of water flux. The simplest way to do this is to adjust the hydraulic conductivity of the GCL to reflect the presence of a geomembrane. (Note: such a simplification does not mimic reality because water flows through a geomembrane via diffusion, and Darcy's law is not applicable to diffusion. Nevertheless, as a matter of computational convenience, one may make estimates of water flux by using appropriate values of equivalent hydraulic conductivity.) Also, Eq. 1 applies to a CCL or GCL liner alone and not to composite liners involving one or more separate geomembrane components. Composite action with a geomembrane is considered later.

The flux ratio for water, F_w, is defined as the flux through the GCL divided by the flux through the compacted clay liner (CCL):

$$F_w = v_{GCL} / v_{CCL} \qquad (2)$$

or:

$$F_w = \frac{k_{GCL}}{k_{CCL}} \frac{T_{CCL}}{T_{GCL}} \frac{H + T_{GCL}}{H + T_{CCL}} \qquad (3)$$

If the flux ratio is ≤ 1, then the GCL is equivalent to the CCL in terms of steady water flux. For example, for a situation with H = 1 ft (0.3 m) and a GCL with:

$$k_{GCL} = 1 \times 10^{-9} \text{ cm/s} = 1 \times 10^{-11} \text{ m/s}$$

$$T_{GCL} = 7 \text{ mm} = 0.007 \text{ m}$$

and a compacted clay liner (CCL) with:

$$k_{CCL} = 1 \times 10^{-7} \text{ cm/s} = 1 \times 10^{-9} \text{ m/s}$$

$$T_{CCL} = 2 \text{ ft} = 0.6 \text{ m}$$

then F_w from Eqs 3 equals 0.3, which means that there would be less water percolation through the GCL than a compacted clay liner -- equivalency is established for these conditions.

Alternatively, one can assume that water flux through the GCL is equal to the water flux through a CCL (i.e., $F_w = 1$):

$$v_{GCL} = v_{CCL} \tag{4}$$

and compute the required hydraulic conductivity of the GCL by substitution in Eq. 4:

$$k_{GCL} \frac{H + T_{GCL}}{T_{GCL}} = k_{CCL} \frac{H + T_{CCL}}{T_{CCL}} \tag{5}$$

to obtain:

$$(k_{GCL})_{Required} = k_{CCL} \frac{T_{GCL}}{T_{CCL}} \frac{H + T_{CCL}}{H + T_{GCL}} \tag{6}$$

Equation 6 may be used to determined the hydraulic conductivity of the GCL necessary to establish equivalency. So long as the job specifications require that the actual hydraulic conductivity be less than the value computed from Eq. 6, equivalency in terms of steady water flux is theoretically guaranteed. The required hydraulic conductivity of the compacted clay liner (k_{CCL}) is almost universally established as 1×10^{-7} cm/s by regulatory agencies in the U.S. The thickness of GCLs (T_{GCL}) varies from product to product, but is typically about 7 mm after hydration at low overburden stress. The head of liquid on the barrier layer is expected to be low in a final cover system; evapotranspiration and the nature of rainfall events makes the buildup of head on the barrier layer much less likely in final covers than in landfill liners. For illustrative purposes, three values of head of water (H) on the CCL or GCL are assumed: 0, 1 inch, and 1 foot. The required hydraulic conductivity of the GCL for equivalent performance to a compacted clay liner in terms of steady flux of water through the liner is computed as follows:

For a 1-ft-thick compacted clay liner:

- $(k_{GCL})_{Required} = 1 \times 10^{-7}$ cm/s for a negligibly small head of water on the liner
- $(k_{GCL})_{Required} = 2 \times 10^{-8}$ cm/s for a water head of 1 inch on the liner
- $(k_{GCL})_{Required} = 4 \times 10^{-9}$ cm/s for a water head of 12 inches on the liner

For a 2-ft-thick compacted clay liner:

- $(k_{GCL})_{Required} = 1 \times 10^{-7}$ cm/s for a negligibly small head of water on the liner
- $(k_{GCL})_{Required} = 2 \times 10^{-8}$ cm/s for a water head of 1 inch on the liner
- $(k_{GCL})_{Required} = 3 \times 10^{-9}$ cm/s for a water head of 12 inches on the liner

As discussed earlier, the hydraulic conductivity of the bentonite component of commercially-produced GCLs is typically ≤ 1 to 5×10^{-9} cm/s. Thus, it is clear that equivalency